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論　文

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進化を続けるジャーナル

テクニカルジャーナル編集委員長
一般社団法人日本UAS産業振興協議会
常務理事　岩田　拡也

2025年がスタート致しました。謹んで新年のご挨拶を申し上げます。

一般社団法人日本UAS産業振興協議会（JUIDA）が発行するテクニカルジャーナルは，ドローン産業の振興に役立つ技術情報を産業界の皆様に提供するために創設されたオンライン技術情報誌で，掲載論文は年々増加を続けておりますとともに，ジャーナル自体も進化を続けております。例えば，昨年2024年は，技術情報の速報性を向上するためLetter制度を新設致しました。その結果，大学等の研究室からの速報性の高い論文の投稿が増加致しました。Japan Drone展でのポスターセッションに大学の研究室から出展し，大学院に進んで論文にまとめ本誌に投稿頂いた例もございました。また，ベンチャーや中小企業の皆様からも論文を投稿頂き，採録となった開発成果をポスターセッションで発表頂いたことで，様々な企業様との連携や商談に繋がった例は，まさに本誌の目指す姿の一つでございます。

今年のJapan Drone2025でも，本誌のポスターセッションを開催致します。企業やスタートアップの皆様には，実証実験や製品開発，サービスやソリューション創出などで得た先進的な取り組みや知見をご発表いただき，商談に結実する機会として，また日本のみならず世界へ発信する広告としてお役立て頂ければ幸いです。もちろん，大学研究室の若き学生の皆様にも，査読付きの論文となりますので奮ってご参加頂き，研究者としての登竜門として頂ければと存じます。

昨年年始の能登半島の大震災で焼けた街並みと，ウクライナや中東の戦争で焼けた街並みは，よく似ているようで人の絆を伴うか人の憎悪を伴うかの点で対局にありますが，どちらもドローンの活用が促進している点に私達の未来への責任を感じます。JUIDAでは，人の絆を伴う前者の災害支援とドローンの関係強化に向けて最大限の取り組みを行っているところです。本誌も，防災とドローンを組み合わせた特集号等を企画することにより，ドローンの技術情報を社会に役立てることができないか模索していきたいと考えております。

ドローンをこのように活用したら現場で役立った，ドローンと何かを組み合わせることで問題を解決できたといった技術情報や実例が多く投稿され，様々な方面に共有されることで本誌も社会や世界に貢献できます。現場で役立ちそうなドローンに関する情報がございましたら，是非奮ってご投稿ください。その一歩一歩の積み重ねが，やがて人々の憎悪の連鎖を断ち切るドローンの活用と，人々の絆を結ぶドローンの活用を生み育てることになるとJUIDAは信じます。本年も何卒宜しくお願い申し上げます。

2025年1月吉日

常務理事
岩田　拡也/Kakuya Iwata
産業技術総合研究所 主任研究員。1998年通商産業省工業技術院電子技術総合研究所に入所。第16回電子材料シンポジウムEMS賞受賞，第12回応用物理学会講演奨励賞受賞。白色LED開発にてゼロから1兆円産業に成長する過程を経験。半導体製造装置開発からロボット技術に目覚め，2004年に独立行政法人産業技術総合研究所知能システム研究部門に移籍，無人航空機の研究開発をスタート。2007年日本機械学会交通・物流部門優秀講演表彰を受賞。2008年に経済産業省製造産業局産業機械課にてロボット政策に従事。2009年以降「NIIGATA SKY PROJECT」の無人航空機開発を立ち上げる。

Letter

脳波計測によるストレス解析のための実機とCGのドローンにおけるディスクレパンシー評価

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近年，Urban Air Mobility（UAM）に関する技術が世界中で研究されている一方，UAMやドローンの社会受容性については十分に検討されていない。そこで著者らが所属する研究グループでは，アンケートによる主観評価と簡易脳波計測にもとづく感性アナライザによる客観評価を組み合わせた社会受容性評価手法を提案した。この手法の有効性は確認されている。2023年12月に実施された便益効果評価実験では，UAMの社会受容性を向上させる手法として場面想定が提案された。しかしながら，得られたデータの信頼性が不十分であったため，適切な実験環境が設定できていない可能性，および十分な場面想定ができていない可能性があった。また，参加者がいくら場面想定を十分にできたとしても，実際のUAMとCGとの乖離は無視し難い。そのため，実験環境を改善することで，実際のUAMとCGのディスクレパンシー（乖離）を小さくする必要がある。本研究では，実際のUAMを用いた実験は困難であるため，ドローン（マルチコプター）を用いてこの種の検討を行う。本発表では，一般の参加者を対象にするのではなく，著者が所属する研究グループの学生を対象に実施された実験について述べる。

Keywords: ディスクレパンシー，脳波計測，感性アナライザ，社会受容性，ストレス，UAM

Discrepancy Evaluation Between Actual and Computer Graphics Drones for Stress Analysis by EEG Measurement

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Technologies related to urban air mobility (UAM) are being studied worldwide. However, the social acceptance of UAMs and drones has not been investigated thoroughly. To address this issue, the authors propose a social acceptance evaluation method that combines subjective assessments by questionnaires with objective evaluations using a Kansei Analyzer based on a simple electroencephalograph. The effectiveness of the proposed method was confirmed. In the benefit-effect assessment conducted in December 2023, scene assumption was proposed as a means of improving social acceptance. However, the reliability of the obtained data was insufficient, and there was a possibility of not preparing an appropriate experimental environment or assuming sufficient scenes. Even if the subject is able to adequately assume the scene, it is difficult to ignore the discrepancy between the actual UAM and CG. Therefore, it is necessary to reduce the discrepancy between the actual UAM and CG by improving the experimental environment. As it is difficult to conduct experiments using an actual UAM, in this study, we used a drone (multicopter) for the investigation. This paper presents the results from a preliminary experiment conducted with students in our research group, rather than with participants from the general public.

Keywords: Discrepancy, EEG measurement, Kansei analyzer, Social acceptance, Stress, Urban air mobility

1. Introduction

Drones are now becoming popular, and industrial drones for logistics and urban air mobility (UAM) for mobile infrastructure are being commercialized. Although there is ongoing research and development on the safety and performance of drones, there has been little research on the social acceptance of the aerial industrial revolution [1]. Social acceptance is generally considered in terms of technical, institutional, and market aspects [2]. However, in this study, it refers to the psychological aspects of the extent of noise and fear accepted by the public. In the past, when new infrastructure was introduced, such social acceptance was not considered seriously. As a result, public protests occurred after airports and high-speed railway lines were built. Although it is necessary to reflect on such experiences, the authors are unaware of any specific evaluation metrics for social acceptance evaluation at present. Therefore, to enable the smooth market introduction of UAM, it is necessary to establish an objective evaluation method for social acceptance, set acceptance criteria, and develop UAM based on such criteria. Hara et al. [3] attempted to objectively evaluate social acceptance by measuring stress levels using an analyzer based on simple electroencephalography.

In addition, according to a psychosocial survey on noise by Yamanouchi et al. [4], it was hypothesized that stress tolerance changes with different applications and stakeholders, even for the same mobility. Furthermore, previous studies reduced the subjective stress measured from drone noise to formulate drone flight operation conditions [5]. However, uniformly setting the noise level and developing drones accordingly cannot necessarily improve social acceptance by citizens or users. Therefore, it is necessary to search for an acceptable noise level for each application and stakeholder. However, such research has not yet been conducted [6]. Takahara et al. [7] conducted a benefit-effect evaluation experiment to clarify the acceptable noise level for each use through the scene assumption method. The results of the experiment showed that the acceptable noise level may be higher when using a UAM with a large social impact compared to daily use vehicles for commuting to work. However, the reliability of the obtained data was insufficient. Therefore, it is necessary to improve the experimental environment and investigate the stress factors. Even if the subject is able to adequately envision the scene, the discrepancy between the real UAM and CG is difficult to ignore. Therefore, it is necessary to reduce the discrepancy between the real UAM and CG by improving the experimental environment. As it is difficult to conduct experiments using a real UAM, in this study, we used a drone for the investigation. We used an analyzer based on simple electroencephalograph (EEG) measurement to evaluate the discrepancy in the stress levels between a real drone and CG drone, and discussed the fundamentals of constructing an experimental environment when using a UAM as a target. In the future, this research aims to contribute to the smooth social implementation of UAM. A preliminary experiment was conducted not with general participants, but with students in the authors' research group. In addition, we summarize the results of a simpler analysis of the preliminary experiment without the weighting described in Section 4-3 in [8].

2. Objective evaluation method using a simple electroencephalograph

Sociopsychological questionnaires are often used to assess emotional changes in social acceptance. However, as these questionnaires are subjective, they cannot accurately capture real-time emotional changes. For the EEG measurement in this study, we employed a Kansei Analyzer (Figs.1 and 2) [9] from Dentsu Science Jam Inc., which is a simple EEG-measuring device designed for emotion measurement. The Kansei Analyzer is a simple electroencephalograph designed to measure five emotional states: stress, concentration, preference, calmness, and interest. Its real-time nature makes it useful for time-series sensitivity assessments. In principle, sensitivity index values are estimated from EEG in real time by pattern matching with a database accumulated over many years such that the feature values based on the EEG shapes and sensitivity index values based on biohormone levels match one-to-one. This is based on the correlation between changes in biohormones related to emotional responses and EEG feature patterns (i.e., hormone fluctuations affect EEG patterns and vice versa).

Fig.1　Kansei analyzer.

Fig.2　Installation method.

3. Stress factors given by drones

To evaluate the stress-level discrepancy between an actual drone and a CG drone, it is necessary to create a CG based on the stress factors imparted by drones to people. In this section, we explain the stress factors that drones cause to people based on related studies. First is the noise, which is considered to be the strongest factor in the stress caused by drones. Unlike other environmental noises (e.g., traffic and aircraft noise), drones generate noise that contains many high-frequency components and pure tones [6]. Owing to this characteristic, drone noise is often perceived as more unpleasant than normal environmental noise. The unpleasantness is amplified by the rapid modulation of sound particularly due to the rotation of the propeller. The second factor is the size of the drone. It has been reported that larger drones have a greater visual presence, and seem more intimidating and dangerous [10]. The third factor is flight altitude. Drones flying at lower altitudes are reported to cause greater concerns regarding noise, safety, and privacy invasion [10]. Finally, the flight speed of the drone is also a factor. Sudden changes in direction and flight at high speeds have been reported to cause stress.

Specifically, at a higher speed, it is more difficult to predict the flight of the drone and there is a greater fear of collision [6]. Based on the aforementioned stress factors caused by drones, we focused on the drone size, which are frequently reported stress factors, and evaluated the stress-level discrepancies between actual drones and CG drones.

4. Experimental method

As a preliminary experiment, we did not involve general participants, but explained the details of the experiment to students (6 students in their 20 s) in our research group, and they consented to cooperate in the experiment.

4-1 Experiment environment and flight path

The actual and CG drones are shown in **Figs.3** and **4**, and the experimental environment and drone flight paths are shown in **Figs.5** and **6**, respectively. The drone weighed 249 g, measured 298 × 373 × 101 mm, had a maximum flight time of 30 min, and a noise level of 70 dB at the closest approach (0.8 m from the subject).

Next, the flight path of the drone is described. The drone ascended from a platform 0.4 m above the ground to a height of 1.2 m over a period of 5 s, approached the subject over a period of 15 s, and stopped 0.8 m in front of the subject. The subjects' EEG data for 20 s up to this point were measured using a Kansei analyzer. The CG drone was created based on the size, noise level, and flight path of the actual drone.

Fig.3 Actual drone.

(A) (B)

Fig.4 (A) CG1 drone (Small), (B) CG2 drone (Large).

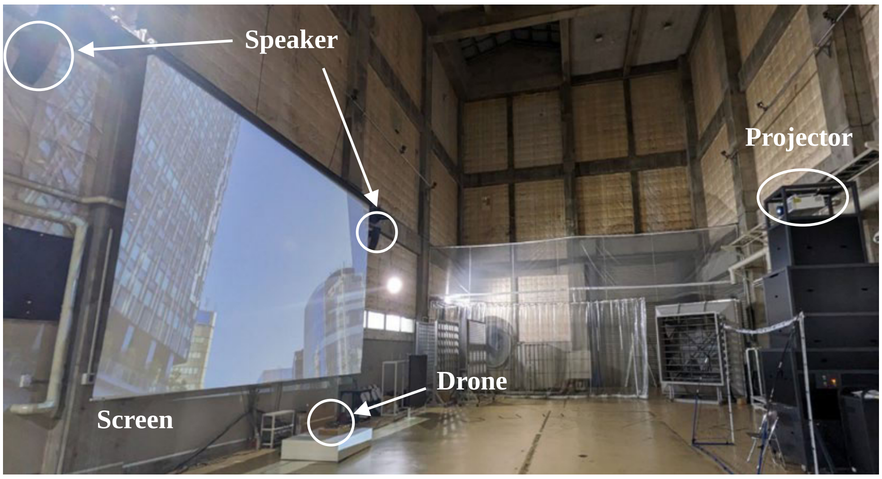

Fig.5 Experiment environment.

4-2 Experimental protocol

The experimental flow is shown in **Fig.7**. The participants were asked to view three types of drones: an actual drone, a CG1 drone, and a CG2 drone with an interval between them to allow for the questionnaire and rest time. To account for the effect of order, each subject viewed the three types of drones in different orders.

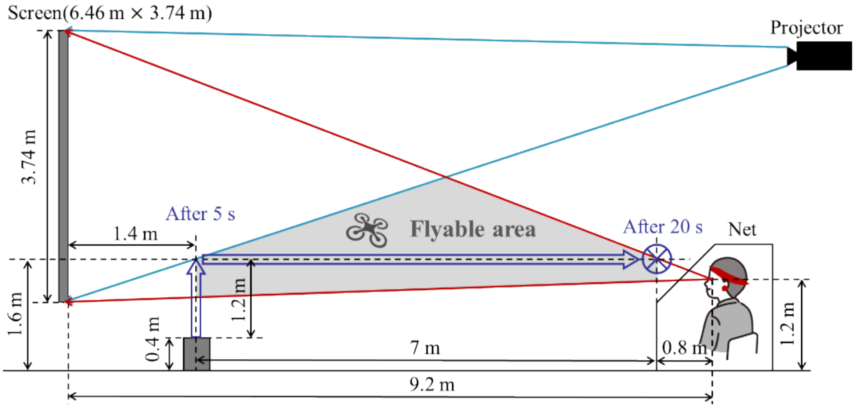

Fig.6　Flight path.

Next, we describe the CG drones. CG1 was a CG-drone that was 2/3 the scale of the real drone, and CG2 was a CG-drone that was 3/2 the scale of the real drone. The CG sounds were recorded from the actual drone flights, processed, and edited. The noise level was measured according to the characteristics of the human ear (characteristic A) [11], which states that human senses become duller for lower loudness and frequency of sound.

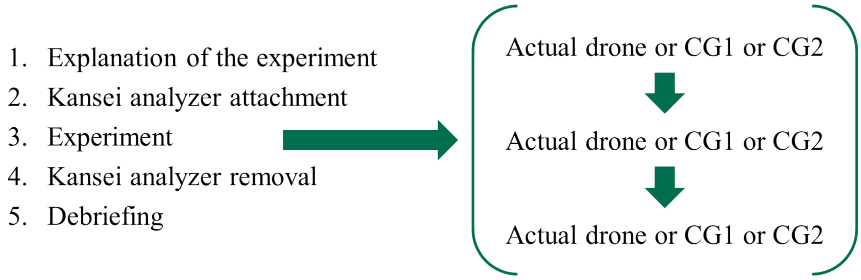

Fig.7　Experimental flow.

4-3　Analysis method

This section describes the analysis method for the stress levels measured using the Kansei analyzer. The discrepancy between the CG drone and real drone was evaluated when the size and noise level of the CG drone were changed. The stress level was measured for 20 s before and after the drone started to fly or when the CG drone started to play its video. The measured data for 20 s before and after the flight were weighted based on the mean and standard deviation of each data point. The data was weighted because it is easier for the stress level to change from 50% to 60% compared to the change from 90% to 100%.

Let us assume a_t as the stress level at time t [s], μ is the mean value, and σ is the standard deviation. Then, the weights w_t are determined according to the following rule.

- $|a_t - \mu| \leq \sigma$, then $w_t = 1$
  - $a_t \rightarrow a_t$
- $\sigma < |a_t - \mu| \leq 2\sigma$, then $w_t = 1.5$
  - $a_t \rightarrow 1.5a_t$
- $2\sigma \leq |a_t - \mu| < 3\sigma$, then $w_t = 2$
  - $a_t \rightarrow 2a_t$
- $3\sigma \leq |a_t - \mu|$, then $w_t = 2.5$
  - $a_t \rightarrow 2.5a_t$

Based on the stress level measured by the Kansei analyzer, the weighted average of the stress level of participant i during the 20 s before and after the start of the flight (or the start of the CG) can be expressed using Eqs. (1) and (2), respectively. Let us assume t_s [s] as the time at which the drone flight starts (or CG starts).

$$\bar{a}_{i,1} = \frac{\sum_{t=t_s-20}^{t_s} w_t a_t}{\sum_{t=t_s-20}^{t_s} w_t} \tag{1}$$

$$\bar{a}_{i,2} = \frac{\sum_{t=t_s}^{t_s+20} w_t a_t}{\sum_{t=t_s}^{t_s+20} w_t} \tag{2}$$

Using Eqs. (1) and (2), the stress variation for drone type j for the i-th participant is expressed by Eq. (3). Note that $j = 0$ is the actual drone, $j = 1$ and $j = 2$ represent CG1 and CG2, respectively.

$$x_i^j = \bar{a}_{i,2} - \bar{a}_{i,1} \ (j = 0, 1, 2) \tag{3}$$

Using Eq. (3), the average variation of drone type j for experimental group k is expressed by Eq. (4), where N_k is the number of participants in each experimental group (A or B).

$$y_k^j = \frac{1}{N_k} \sum_{i}^{N_k} x_i^j \ (j = 0, 1, 2, k = A, B) \tag{4}$$

Using Eq. (4), the discrepancy value between the actual drone and CG drone in experimental group k is expressed by Eq. (5).

$$D_k^j = \left| y_k^j - y_k^0 \right| \ (j = 1, 2, k = A, B) \tag{5}$$

In Eq. (5), the drone type with a smaller value is interpreted as having a smaller discrepancy with the real drone. By improving the CG such that D_k^j approaches zero, we can develop a social acceptance simulator to evaluate an appropriate level of stress.

5. Experimental results and discussion

5-1 Experimental results

In this experiment, due to the small number of participants and the focus solely on drone size, only experimental group A is considered. Average stress variation values for all drone types and the distribution of the stress variation shown in **Fig.8** and **Fig.9**, respectively. The deviation values calculated from **Fig.8** are $D_A^1 = 3.18$ and $D_A^2 = 1.04$, indicating that the larger CG drones have smaller deviation values than the smaller CG drones. However, as there is no y_A^0 (actual drone) between y_A^1 (CG1) and y_A^2 (CG2), it is difficult to set the deviation from the actual drone to zero by changing the size of the CG drone. In the distribution of the stress variation for CG1 shown in **Fig.9**, one participant exhibited an unusually high value (16.7%), which significantly influenced the average stress variation value for CG1. According to the questionnaire responses, this participant reported having more frequent interactions with drones in daily life compared to the other participants and indicated feeling no stress toward any of the three drone types viewed during the experiment. Therefore, it is inferred that when viewing CG1, the participant may have experienced heightened stress related to factors other than the drone itself, such as the presence of others or tension in the experimental setting.

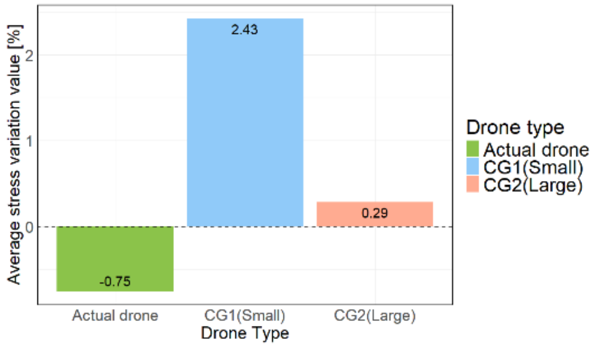

Fig.8　Average stress variation values (N=6).

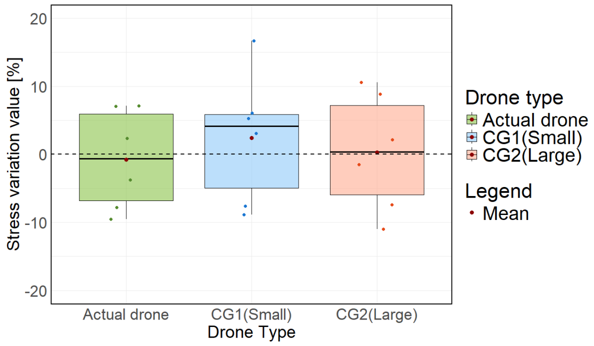

Fig.9　Distribution of the stress variation (N=6).

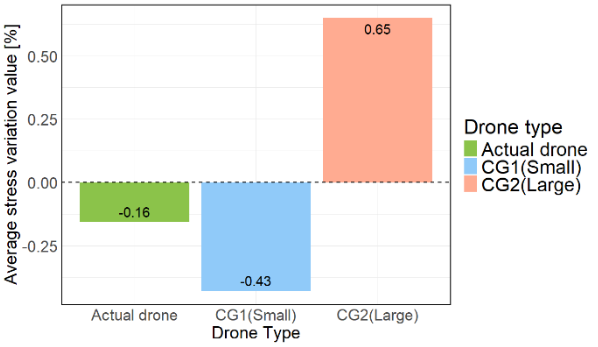

Fig.10　Average stress variation values (N=5).

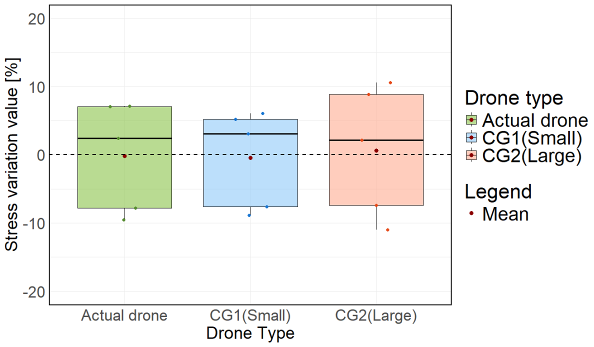

Fig.11　Distribution of the stress variation (N=5).

5-2　Discussion

As mentioned in Section 5-1, the participant who exhibited an unusually high stress change value for CG1 likely experienced significant stress from factors unrelated to the drone itself. Since the primary aim of this experiment is to evaluate the discrepancy between the actual and CG drones based on stress levels, it cannot be confidently stated that the data from this participant, with an extremely high stress variation value for CG1, are entirely reliable. Therefore, **Figs.10** and **11** present the average stress variation values and the distribution of stress variation after excluding the data from this participant. The deviation values calculated from **Fig.10** are $D_A^1 = 0.27$ and $D_A^2 = 0.81$, indicating that the smaller CG drones have smaller deviation values than the larger CG drones. Furthermore, because y_A^1 (CG1) and y_A^2 (CG2) encompass y_A^0 (actual drone), it is suggested that adjusting the size of the CG drones could bring the deviation value closer to zero. However, because there is no guarantee of a linear relationship between the size of the CG drones and stress levels, the data from **Fig.10** only indicates that the average stress variation value for the actual drone lies between those for CG1 and CG2. Therefore, it is necessary to explore methods for reducing the deviation value by conducting experiments with an increased variety of CG drones of different sizes.

In this experiment, the small sample size led to individual participant data significantly influencing the overall results. As shown by comparing **Figs.8** and **10**, the differences in sample size caused substantial variations in the outcomes. Therefore, we believe that increasing the sample size in future experiments will yield more reliable results, less affected by individual data points. If similar results to those in **Fig.10** can be obtained with a larger sample, it may be possible to adjust the size of the CG drone to reduce the deviation from the actual drone. Moreover, if the deviation can be minimized to near zero, it will open the possibility of developing a simulator capable of accurately assessing the stress levels associated with drones.

Contrary to the hypothesis that the average stress variation for an actual drone would be positive, the experiment produced negative values. This may be due to the fact that many participants were recruited from within the laboratory and were already familiar with drones, leading to a reduced sense of stress. Additionally, it is possible that the stress from the pre-experiment tension exceeded the stress induced by the drone flight.

6. Future prospects

The results of this experiment suggest that it is feasible to design an appropriate experimental environment for researching the social acceptance of next-generation aerial vehicles. These findings indicate that it may be possible to develop an experimental setup to investigate the effects of stress, even with drones replacing flying vehicles. However, the results of this study were significantly influenced by the sample size and the fact that participants were already familiar with drones in their daily lives, which limits the definitive conclusions that can be drawn. In future experiments, we plan to increase the sample size and target individuals unaccustomed to drones in their daily lives. This approach is expected to yield more reliable results than those obtained in this study. Additionally, while this experiment compared the actual drone with CG1, a small-scale CG drone, and CG2, a large-scale CG drone, future studies should include a CG drone of the same size as the actual drone. This would allow an investigation into whether there is any inherent discrepancy in the stress levels between the actual and CG drones. By incorporating a same-size CG drone, researchers could assess not only the presence of discrepancies but also how to adjust the size of CG drones to minimize deviations from the actual drone. Furthermore, evaluating the discrepancies by varying both the size and noise levels of the CG drones could offer new insights and deepen our understanding of the factors influencing the social acceptance of UAM.

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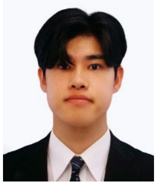

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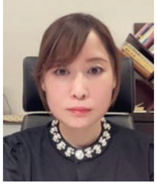

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Letter

映像伝送中継局向け固定翼 UAV における旋回半径偏差と機首方位角を用いた高精度旋回経路追従制御技術の研究

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室蘭工業大学大学院

近年，無人航空機（UAV）は，様々なサービスへの利用が広がっている。中でも固定翼 UAV は長時間飛行や広域観測に有利である。固定翼 UAV の利用例の 1 つである，無線中継局を実現するには指定した円経路に沿って正確に旋回し続ける必要がある。そこで，本稿では固定翼 UAV の旋回半径制御系と機首方位角制御系から構成される新たな高精度旋回経路追従制御系を提案し，6 自由度シミュレーションによりその制御系が正常に動作することを確認するとともに，さらに飛行実証を行った結果を報告する。

Keywords: 固定翼 UAV，旋回，ロール角，方位角，飛行実証

Highly Accurate Turn Path Tracking Control Technology for Fixed-wing UAV Using Radius Deviation and Nose Heading Angle to Realize Video Transmission Relay Station

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Unmanned Aerial Vehicles (UAV) have recently been used to provide many kinds of services, among them fixed-wing UAVs are advantageous for long flights and wide-area observations. In order to realize wireless relays station by the UAV, the UAV should continue to accurately turn along a predetermined circular path with its radius specified. To realize the path, we propose a new turn path control system that consists of radius deviation control and nose heading angle control on the UAV, and describe simulation results by which it is confirmed that the proposed control system worked well. And finally, we describe results of the flight verification experiment.

Keywords: Fixed-wing UAV, turning, roll angle, yaw, Flight verification

1. Introduction

In recent years, the use of unmanned aerial vehicles has advanced, and research and development are underway to provide future services in the fields of agriculture and forestry, such as crop pest control, farmland monitoring, surveying disaster areas, terrain measurement, transporting supplies, and radio relay for securing communication links [1]. In this situation, we have proposed a video transmission relay system using a fixed-wing UAV as a relay station, as shown in Fig.1. Currently, multi-copters, which are rotary-wing UAVs, are often used for observation. On the other hand, fixed-wing UAVs are more advantageous when observing large areas over long distances in a short period because they have a long endurance. Focusing on its long endurance, fixed-wing UAVs can be used as a wireless relay station for the video transmission relay system by making it turn along a predetermined circle path accurately and continuously. There are many papers on turning techniques. For example, in paper [2], flexible path following is essential when fixed-wing UAVs are used for various missions such as surveillance and disaster applications, so they aimed to follow complex paths, including curves, and confirmed their performance through both simulations and flight experiments. Also, in paper [3], a method is proposed to generate a turning path for a fixed-wing UAV without sacrificing maneuverability and safety, with the goal of enabling the fixed-wing UAV to safely perform its mission in a confined space. Also, in paper [4], a control method for rapid direction change is proposed for the purpose of carrying out missions such as surveillance and search and rescue without compromising the advantages of fixed-wing UAVs, such as high speed. However, none of them describe how to make the UAV turn along the predetermined circular path accurately and continuously.

Therefore, we propose a new turn path tracking control system that makes use of the target nose heading angle and turning radius. By using the control system, at first, computer simulations were carried out for small fixed-wing UAV so as to confirm its validity. Then, flight experiment was conducted to verify the control system.

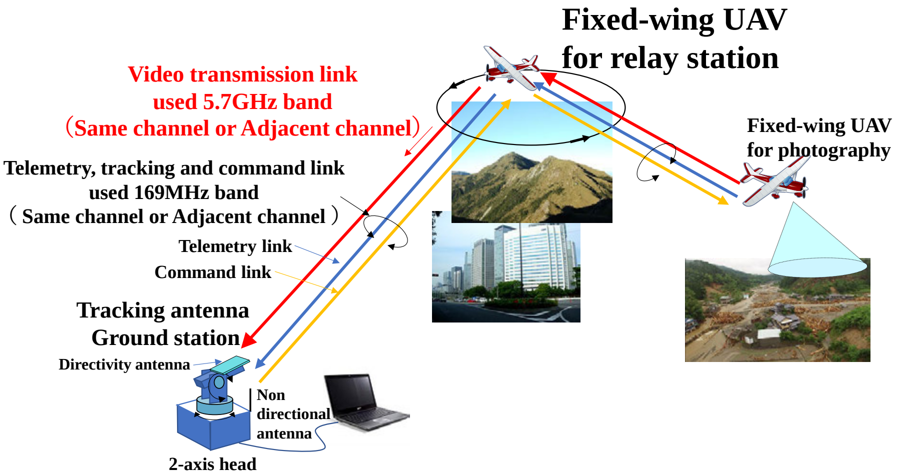


Fig.1 Image of video transmission relay system using fixed-wing UAVs.

2. Conventional turn path control and problems

The authors aimed at achieving highly accurate turn path tracking by using two control systems. One is a roll angle control system focusing on lateral force balancing by aileron operation. The other is a turn radius control system of which rudder command is given by the difference between the target turn path radius and the actual turn radius [6]. After confirming the validity of the method by computer simulation, the flight experiment was carried out as shown in Fig.2. The red line shows the turning trajectory, which deviates significantly from the target path shown in black. The reason is that as the roll angle control system and the turning radius control system were designed independently, when the vehicle deviates significantly from the target turn path, the force generated by the roll angle control system offset the force generated by the turn radius control. That is to say, when the UAV is located inside the target turn path, the force by the roll angle of which radius path is cancelled out by the force of the rudder angle, resulting in the turn radius which is larger than that of the target turn path.

In the same way, when the UAV is located outside the target turn path, the force generated by the rudder is added to the force generated by the roll angle, therefore, that results in a small turn path.

In addition, even though the simulation was successful in turning in the method we proposed [6], the successful accurate turning could not be reproduced in the flight verification experiment. We confirmed that this is due to the expansion of the initial deviation caused by the delay in the control system that occurs immediately after the start of the turn. In fact, simulations performed with our methods, do not take initial deviations into account. Therefore, this time, the proposed methods simulations including initial deviations we carried out to confirm convergence.

From above results, it is clarified that it was necessary to consider the balance adjustment between the roll angle control system and the turning radius control system which uses the rudder. Before investigating the method to design the balance adjustment, we explored to realize a highly accurate turn path tracking system by only roll angle control system based using deviation of both turn radius and heading angle.

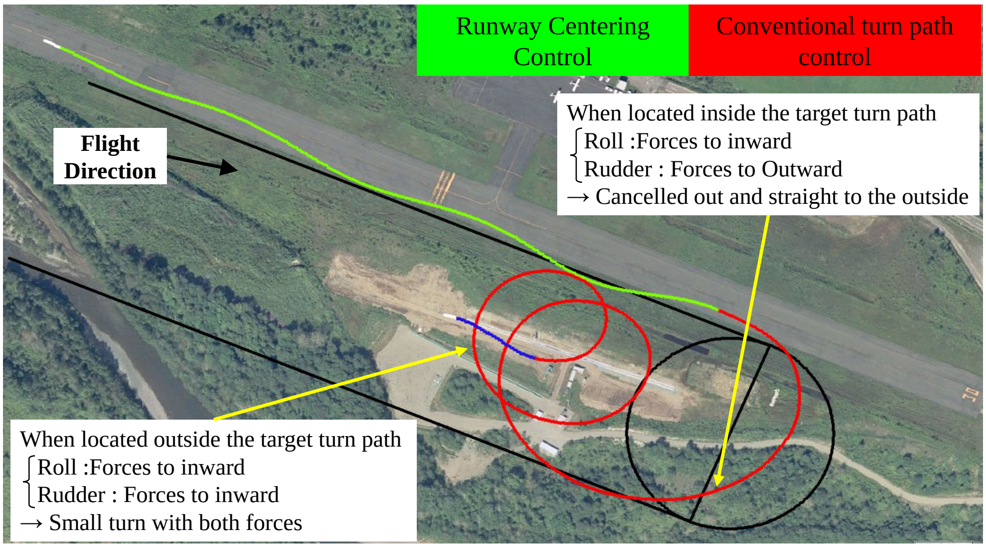


Fig.2　Flight experiment at shiraoi gliding port by conventional turn path control [6] technology.

3. Proposal of highly accurate turn path tracking control method

3-1　Control system policy and configuration

We propose a new control system to track the turning path accurately, which consists of a turn radius control system and a nose heading angle control system. Both control systems use the roll angle control system. The commands to the nose heading angle control system are a sum of two kinds of nose heading angle. One is the ideal nose heading angle ψ_{tan}, which is measured from true north to which the airplane should be directed corresponding to position of the airplane. The other is the nose heading angle ψ_{cmd} which is calculated by the deviation from the target radius R_{cmd} and the actual radius R. The sum of these nose heading angles is converted to roll angle command ϕ_{cmd} through PID parameter. Therefore, the turn radius control system is incorporated as an outer loop of the nose heading angle control system to reduce the turn radius deviation to zero and the roll angle control system is incorporated into the inner loop of the nose heading angle control system as shown in Fig.3.

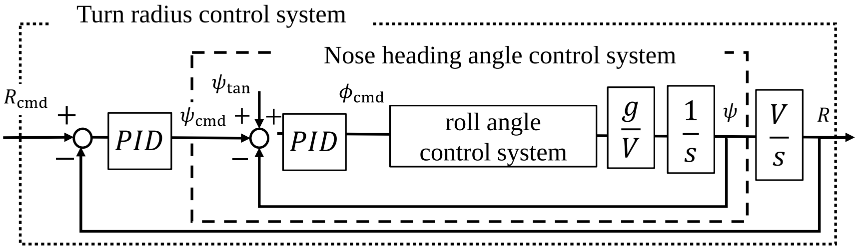


Fig.3 Block diagram of turn path tracking control system.

3-2 Relationship between turning radius deviation and nose heading angle

From **Fig.4**, after a radius deviation ΔR is defined as a difference between the target turn radius and the actual turn radius, from **Fig.4** the relationship between the radius deviation ΔR and the nose heading deviation $\Delta\psi$ measured from the line parallel to the tangent line of the turn circle can be expressed as shown in Eq. (1)

$$\Delta\dot{R} = V_L \sin\Delta\psi \tag{1}$$

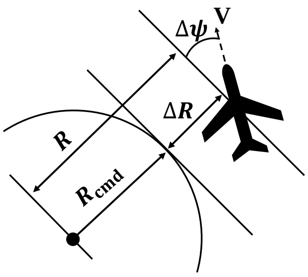


Fig.4 Relationship between turning radius and nose heading angle.

3-3 Derivation of ideal nose heading angle ψ_{tan}

Next, the ideal nose heading angle ψ_{tan} at the current position of the airplane is derived. First, in **Fig.5**, l_1 is the line connecting the turning center and the current position of the airplane, l_2 is the tangent line at the intersection of l_1 with the target turning path, and l_3 is the line extending to the true north direction from the turning center. The angle between the x-axis and the true north is ε.

The ideal nose heading angle ψ_{tan} is the angle between l_2 and l_3. To obtain the ideal nose heading angle ψ_{tan}, first it is necessary to determine the inclination θ of l_1. The angle θ can be derived from the current position (x_t, y_t) and x coordinates axis with the center of circle as its origin as shown in Eq. (2). Next, the angle λ between the tangent l_2 and the x coordinate axis can be derived as shown in Eq. (3) using the angle θ.

$$\theta = \tan^{-1}\left(\frac{x_0 - x_t}{y_t - y_0}\right) \tag{2}$$

$$\lambda = \theta + \frac{\pi}{2} \tag{3}$$

From the above, the ideal nose heading angle ψ_{tan} can be derived as shown in Eq. (4) using the angle ε between the x coordinate axis and the true north, and the angle λ in Eq. (3).

$$\begin{aligned}\psi_{tan} &= -(\lambda + \varepsilon) \\ &= -(\theta + \tfrac{\pi}{2} + \varepsilon)\end{aligned} \tag{4}$$

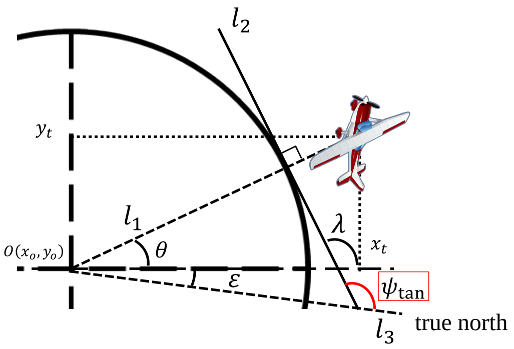


Fig.5 Tangent angle on the target path obtained from the flight position.

4. Simulation

The validity of the proposed turn path tracking control system is evaluated by computer simulations. In simulations, all actual control systems such as velocity control system, altitude control system and the turn path tracking control system are incorporated. All controller in those control systems use PID elements. Also, the feedback rate for simulation is 25 [Hz].

4-1 Controlled airplane

Assuming the flight experiment, data of an actual model airplane are used. The airplane is a low-wing type one and driven by fuel engine and has a mass of about 5.5 kg, a total length of 1.7 m, and a wingspan of about 2 m. The picture of the model airplane is shown in **Fig.6**.

Fig.6 Model airplane.

4-2 Simulation conditions

At first, the aircraft will fly in a straight line for 50 seconds to keep the airplane stable before entering into a circling flight. In the simulation, the turn radius, the altitude and the air velocity are targeted to be those as shown in **Table 1**. Besides, the criteria to judge whether the proposed control system works well is set in advance. For the first circle, the deviation of the turn radius is set to within ±14 m, which is 20% of the target radius, by taking into account for the transition such as rise-up and overshoot in control systems. For the final circle, the deviation is set to be ±6 m, taking into account the sensor errors used onboard systems of the actual model airplane. Those errors are specified as standard deviations shown in **Table 2**.

Simulations were carried out for following three conditions to confirm the convergence of the control system. The first is a no-wind condition. This was conducted to verify the stability of the control system. The second is a steady wind (3 m/s) condition parallel to the x coordinate axis. This was conducted to verify the performance in a disturbing wind environment. The third is the condition that has an initial deviation of 10 meters to confirm the performance of the convergence.

Table 1 Simulation conditions.

Target turning radius	70 m
Target altitude	100 m
Target air velocity	25 m/s

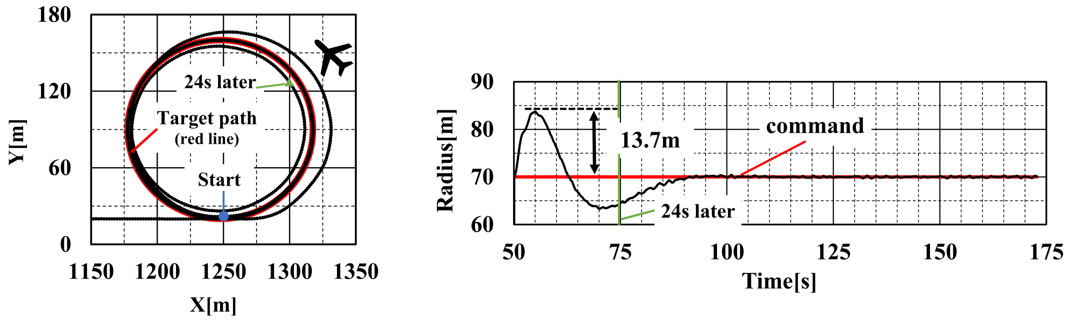
Table 2 Sensor error.

Attitude angle	0.5 deg.
X, Y direction	3 m
Altitude	0.2 m
Velocity	0.17 m/s

4-3 Simulation results

The flight trajectory obtained from the simulation and the time histories of the turning radius are shown below. Also, while the flight trajectory is expressed in three dimensions in Reference 6, it is expressed in two dimensions in this paper to make the trajectory at the time of turning easier to understand.

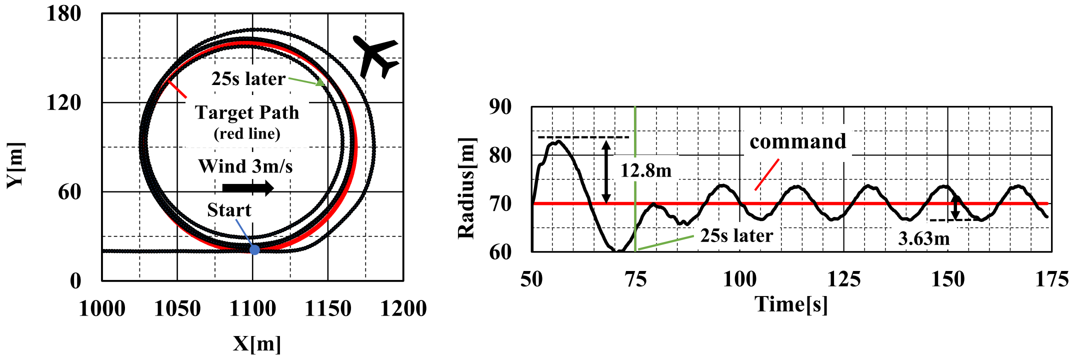
At first, simulations were carried out under no wind conditions shown in **Fig.7**. From **Fig.7**, the maximum turn radius deviation for the first circle was 13.7 m and the radius converged to ±0.6 m in about 24 s from the start of the turn, which was within the target value.



(a) Flight path **(b)** Time histories of the turning radius

Fig.7 Simulation results (no wind).

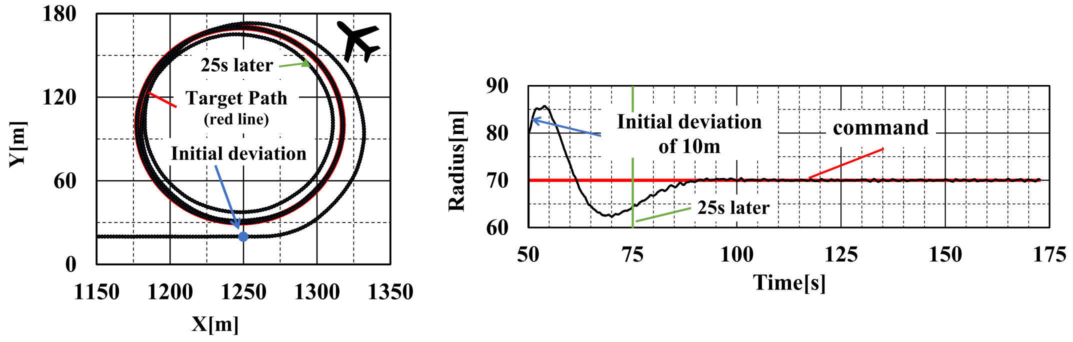
Then simulations were carried out for a steady wind of 3 m/s as shown in **Fig.8**. From **Fig.8** the maximum turn radius deviation for the first circle was 12.8 m, and the final deviation was 3.6 m, which was within the target range. It was also confirmed that the radius converged within ±6 m of the target radius in 25 s from the start of the turn.



(a) Flight path **(b)** Time histories of the turning radius

Fig.8 Simulation results (steady wind of 3 m/s).

Finally, the simulation was performed with an initial deviation of 10 m as shown in **Fig.9**. From **Fig.9**, it was confirmed that the radius converged within ±6 m of the target radius in 25 s from the start of the turn.



(a) Flight path　　**(b)** Time histories of the turning radius

Fig.9　Simulation results (initial deviation of 10 m with no wind).

5. Flight verification experiment

A flight verification experiment was conducted using the proposed control system. The target airplane (Fig.6), same as simulation, was mounted with a microcontroller board and an autonomous control program written in C language was executed. Also, the feedback rate is 25 [Hz], the same as simulation. The airplane first follows a straight path and after passing a given point switches to a turning flight to follow a circular path with a radius of 70 m. The airplane then flew to follow a straight path in the opposite direction after completing 5.5 laps of turning flight. The actual flight path results are shown in Fig.10 and the time history of the turning radius is shown in Fig.11. From Fig.10, it can be found that all flight phases follow the target turn path. Fig.11 shows that the turning radius generally follows the command, although there is some vibration around target of 70 m. Also, the average deviation of the radius was 7 m throughout the turn flight. This result was satisfactory considering the sensor error used, control error.

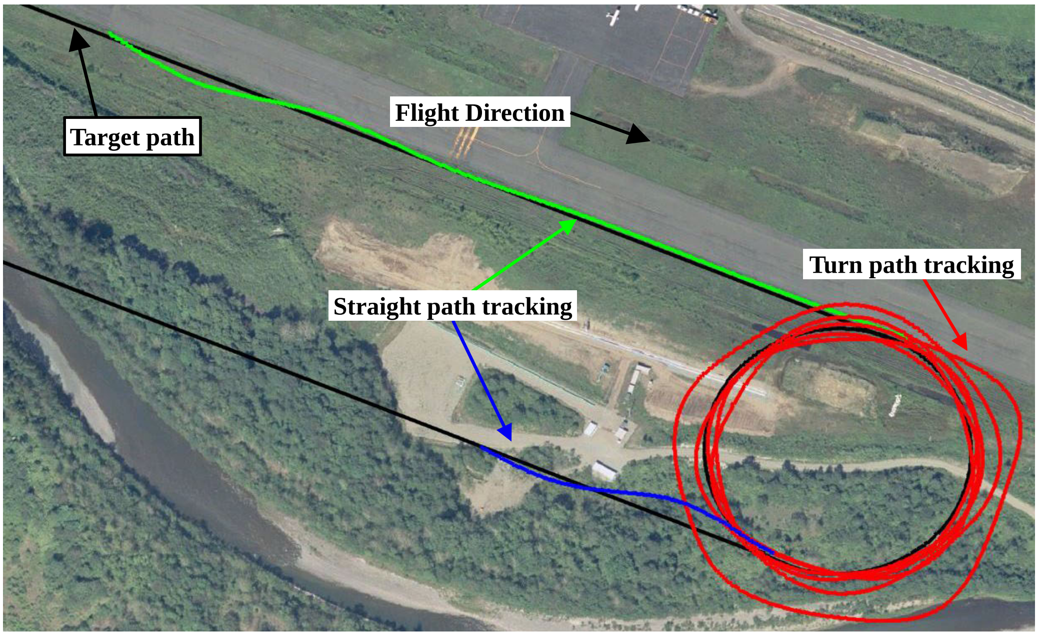


Fig.10　Flight experiment.

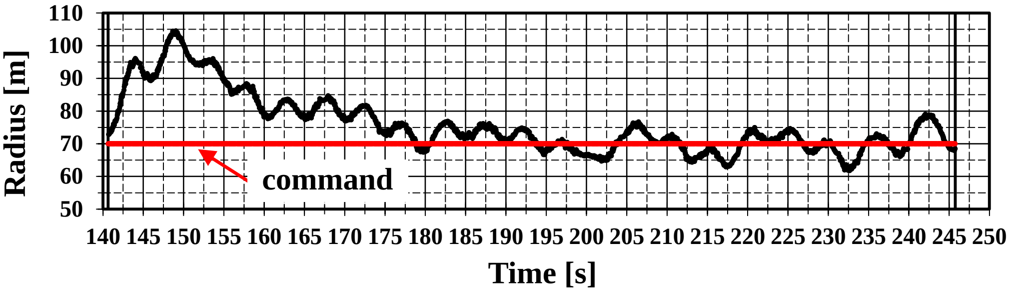


Fig.11 Time history of turning radius.

6. Conclusions

To realize highly accurate turn path tracking, we proposed a new control system to use radius deviation and nose heading angle. The feature of the proposed control system uses two nose heading angles derived from the current position of the airplane and the radius deviation. After simulations, it was confirmed that the airplane could turn within the target deviation against the target turn radius under no wind and a steady wind of 3 m/s.

Finally, flight verification experiment was conducted using the proposed control system, and a stable turn of 5.5 laps was achieved.

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Strategical Perspectives on Market Entry of Urban Air Mobility (UAM) in Japan

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This paper explores the market penetration of urban air mobility (UAM) in Japan, a rapidly developing field with the potential to revolutionize transportation in cities worldwide. While there is significant interest in exploring the possibilities of UAM in Japan, its successful implementation requires the consideration of various factors, such as sustainability goals, social acceptance, and the creation of a suitable ecosystem. This research aims to provide insights into the key strategic considerations for UAM stakeholders seeking to enter and penetrate the Japanese market, as well as how these considerations differ for new entrants compared to established companies.

Keywords: Urban Air Mobility (UAM), Market Penetration, Sustainability, Social Acceptance, Ecosystem Creation, Strategic Considerations, Regulatory Environment, Japan Cultural Context, UTM, UAM, Drone, Mobility

1. Introduction

Urban air mobility (UAM) is a rapidly developing field with the potential to revolutionize transportation in cities around the world. In Japan, a country with a highly developed transportation infrastructure and a keen interest in technological innovation, there is significant interest in exploring the possibilities of UAM. The Japanese government has already taken steps to encourage the development of UAM, such as establishing the public-private UAM promotion council in 2018 [1]. To ensure the successful implementation of UAM in Japan, it is crucial to consider factors such as social acceptance, sustainability goals, and the development of a comprehensive ecosystem and effective market penetration strategy.

The study of urban air mobility and the development of ecosystem and market penetration strategies are becoming increasingly important as cities seek more sustainable and efficient transportation solutions. Japan, with its highly urbanized environment, is a promising market for UAM. This paper aims to contribute to the existing body of knowledge by exploring the key considerations for UAM stakeholders seeking to enter and penetrate the Japanese market.

To achieve these objectives, this study seeks to answer two fundamental research questions:

1. What are the unique challenges and opportunities for UAM stakeholders seeking to penetrate the Japanese market, and what strategies can they adopt to promote buy-in and foster a sense of collective responsibility in Japan?
2. What are the key strategic considerations in terms of the ecosystem for UAM stakeholders seeking to integrate with Japan's existing transportation network, and how do these considerations differ for new entrants such as start-ups compared to established companies?

Through qualitative analyses, this research aims to contribute to the understanding of the challenges and opportunities for UAM in Japan and shed light on how UAM can fit into Japan's existing transportation network and address its particular challenges.

2. Literature review

2-1 Theoretical framework

The theoretical framework for this literature review focuses on several key concepts: urban air mobility (UAM) within the mobility as a service (MaaS) paradigm, transportation innovation, technological advancement, and societal change.

UAM refers to the concept of using vertical take-off and landing (VTOL) aircraft to provide on-demand transportation services in urban areas. It is a trending research topic globally [2] and is closely monitored by major consulting firms [3,4].

Transportation innovation is critical for UAM, involving the development of new technologies and business models to make UAM a reality [5]. Technological advancements are essential for creating safer, more efficient, and more affordable aircraft and infrastructure. Societal change and social acceptance are also crucial, as UAM requires shifts in attitudes and behaviors towards transportation and urban development [6,7].

2-2 UAM ecosystem

An ecosystem, as defined by Armour, includes a wide range of stakeholders such as city, regional, aviation, and environmental authorities, as well as drone and air taxi operators, all crucial for UAM's successful planning, integration, and operation [8]. This ecosystem encompasses government agencies, transportation authorities, aviation and environmental authorities, and UAM operators [9]. Companies like Volocopter and E-Hang have issued white papers outlining their ecosystem strategies [10,11].

2-3 Sustainability goals and social acceptance

Sustainability is a critical consideration for UAM development, given the aviation industry's contribution to greenhouse gas emissions [12]. Battery technology, although promising due to breakthroughs in energy density, still presents challenges in terms of environmental impact and recycling [13,14].

Social acceptance is vital for UAM's success. Public perception, including concerns about noise pollution, safety, and privacy, plays a significant role in UAM adoption [7,3]. Ensuring social fairness is also important, as highlighted by the scaling model's impact on public acceptance [15].

2-4 Market penetration strategy and ecosystem creation

Successful UAM services depend on effective market penetration and ecosystem creation strategies. Various studies have examined these strategies, identifying opportunities for UAM providers to gain market share and create viable ecosystems [16]. In Japan, studies have identified distribution and cultural challenges, such as high entry costs and close business linkages, as significant barriers to market entry [17].

2-5 Market size references

As of September 2021, Japan's helicopter market was valued at approximately $700 million USD (Statista, n.d.). In fiscal year 2020, Japan's aviation industry supported over one million jobs and contributed nearly $83 billion to GDP [19]. The UAM market is projected to reach 2.5 trillion yen by 2040, assuming significant expansions in the aviation and travel markets [20].

2-6 Innovation and government initiative in Japan

Japan has a history of technological innovation, driven by government initiatives such as the Science and Technology Basic Plan [21]. In the context of UAM, METI has published a roadmap for UAM development, regularly updated to guide the industry's growth [22]. Japan's strong manufacturing sector, including battery and motor companies, plays a crucial role in UAM's supply chain development [23].

Japan is also investing in sustainability, focusing on clean technologies and the environmental impact of new products [24]. Despite these initiatives, Japan faces challenges such as an aging population, which affects the workforce and economy [25].

3. Research methodology

3-1 Research design and approach

An exploratory case study approach was chosen to investigate the strategy for implementing UAM in the Japanese market. This approach allows for a comprehensive understanding of the social, cultural, and economic factors affecting UAM implementation in Japan.

3-2 Questionnaire rational

Data were collected through semi-structured interviews, covering four main parts related to UAM implementation in Japan: Japanese innovation, sustainability goals, social acceptance, ecosystem creation, and market penetration strategy.

3-3 Data collection methods

A total of 21 interviews were conducted with various stakeholders, including OEMs, operators, research institutes, trading companies, insurance providers, and others. Interviews were recorded and transcribed, ensuring a broad perspective on the Japanese UAM ecosystem. The interviewees were carefully selected from organizations that play important roles in the Japanese Urban Air Mobility (UAM) ecosystem. This includes trading companies, OEMs, operators, academics, local government entities, insurance companies, and banks. Each of these stakeholders contributes uniquely to the ecosystem—through financing, vehicle design, operations, regulatory development, infrastructure support, public acceptance initiatives, and funding. Their collective insights provide a broad and comprehensive understanding of the challenges and opportunities in UAM development. This selection was made to ensure a holistic perspective, fostering collaboration and supporting the creation of an integrated framework for the safe and sustainable growth of UAM in Japan.

Table 1 Definition of the acronyms in Table 2.

Acronyms	Meaning
OEM	One Equipment Manufacturer
RI	Research Institute
OP	Operator
TC	Trading Company
BK	Bank
INS	Insurance
MC	Municipality
0^{TH}	Others, Maintenance, Building Manufacturer, Drone Company

Table 2 Overview of interview partners.

Acronym	Classification	Role of Interview Partner	Interview Duration (min)	Location	Interview Date (dd.mm.yy)
OEM 1	Helicopter Firm Established	Senior Maneger(*)	110	On-site	23.11.2022
OEM 2	UAM Firm: New Entrant	Director	48	On-site	30.11.2022
OEM 3	Helicopter Firm: Established	Vice-President, CTO	65	On-site	02.12.2022
OEM 4	UAM Firm: New Entrant	CEHR, HR Manager(*)	46	Online	02.12.2022
OEM 5	Helicopter UAM Firm Established	Strategy Manager	40	Online	09.12.2022
RI 1	Academician Expert	Emeritus professor	53	On-site	29.11.2022
RI 2	Academician Expert	Ph.D. Executive Advisor, Fonner Professor	60	On-site	01.12.2022
RI 3	Academician Expert	Urban Air Mobility Research laboratory UAM Startup CEO & Head Airframe Head Airframe	66	Online	15.01.2023
RI 4	Academician Expert	Project Associate Professor	54	Online	15.01.2023
OP 1	Operator Established Airliner	Air Mobility Project Director	67	On-site	01.12.2022
OP 2	Operator Established Airliner	Air Mobility Creation Leader	65	Online	30.01.2023
OP 3	Operator Established Helicopter Operator	CEO(*) Head Marketing, OEM company	57	On-site	02.02.2023
TC 1	Trading Company New Entrant in UAM business	Assistant General Manager (*)	61	On-site	01.12.2022
TC 2	Trading Company	Leader, New Entrant in UAM business	54	Online	21.12.2022
MC 1	Municipality: Prefecture	Digital Business Promotion Division Leader (*)	58	Online	15.12.2022
BK 1	Investment Bank	Vice President	60	On-site	02.12.2022
IN 1	Insurance Company	Managers (*)	69	On-site	02.12.2022
PR 1	Press Agency: Journalist	Deputy Editorial Director, Digital	54	Online	03.02.2023
OTHI	Others: Maintenance Company	General Manager, Adviser(*)	59	On-site	30.11.2022
OTH2	Others: Airport Building Manufacturing Company	Assistant General Manager, Sales representative (*)	38	On-site	01.12.2022
OTH3	Others: Drone Company	CTO	43	Online	30.11.2022

Note that (*) indicates that the interview was conducted with two interview partners.

3-4 Data analysis methods

Qualitative content analysis was used for data analysis, focusing on stakeholders' perceptions and experiences regarding social acceptance and strategic considerations for UAM integration into Japan's transportation network.

4. Findings

4-1 Challenges & opportunities to the implementation of UAM in Japan

By exploring both the challenges and opportunities, this section aims to provide a comprehensive understanding of the UAM market in Japan. Additionally, the section will examine strategies that UAM stakeholders can adopt to promote buy-in and foster a sense of collective responsibility among stakeholders in Japan.

4-2 Identified challenges among the study stakeholders' group

4-2-1 Cultural and social challenges

A Press Journalist (PR 1) noted, "Fifty years ago, we had nothing. After World War II, our society and cities were destroyed... There were a lot of risk-takers and many entrepreneurs like the founder of HONDA, SUZUKI, Panasonic, and SONY." However, today, the environment has shifted to a risk-averse mentality, focused on safety and comfort. This sentiment is echoed by a trading company manager (TC2): "Innovative approaches appear conservative to us... it is not in the culture to try new things like this (UAM) before the others."

4-2-2 Social acceptance

The perception of flying vehicles as exclusive and inaccessible is a significant barrier. An academic (RI1) remarked, "Social fairness is a significant issue in Japan... there is significant opposition from shareholders and the general public towards companies owning business jets." The general public views flying as an infrequent activity, making air travel seem distant and inaccessible. An operator (OP 1) mentioned, "The general public feels that flying is something they do once a month or once a year."

4-2-3 Regulatory challenges

The lack of a regulatory framework is a significant obstacle. A director of an investment bank (BK1) highlighted, "If the FAA and EASA are doing the rulemaking... it is impossible for Japan to take the lead in this area." This sentiment is echoed by an OEM (OP2): "The need for regulations around low altitude utilization... is essential for the successful implementation of UAM." Additionally, Japan lacks regulatory expertise, and stakeholders are concerned about the country's ability to develop UAM regulations independently.

4-2-4 Technological challenges

Technological limitations, particularly battery and technology issues, pose additional challenges. An OEM participant (OEM3) noted, "The most problematic part of UAM is the battery. Once the battery issue is resolved, UAM can be put into practical use." Achieving sustainable mobility requires addressing the entire lifecycle of the battery to minimize environmental impact.

4-2-5 Market demand and economic challenges

Demand, profitability, and cost are significant concerns. Japan's relatively low traffic congestion and stable population growth reduce the perceived need for UAM solutions. An investment bank vice-president (BK1) observed, "In Japan, there are not enough traffic jams to justify the use of those taxis." This challenge is compounded by the need to achieve a competitive price point while ensuring profitability. An academic expert (RI4) stated, "There are not many customers willing to pay for a vehicle that is more expensive than a taxi."

4-3 Identified opportunities among the study stakeholders' group

4-3-1 Government leadership and incentives

Government leadership and incentives play a crucial role. An academic (RI1) observed, "Support from local governments is necessary." Public-private partnerships can help finance UAM infrastructure projects. BK1 emphasized, "In order to guarantee the top-line revenue, local governments will likely need to provide some level of assurance... public-private partnerships such as PPP, PFI, and private finance initiatives will likely be necessary."

4-3-2 Social benefits and cultural motive

UAM has the potential to provide social benefits and foster regional development. Stakeholders emphasized the importance of using UAM for emergency medical services and disaster relief, which could enhance social acceptance. An operator (OP2) suggested that UAM could solve regional social issues and contribute to economic growth by creating employment opportunities and attracting new residents. OEM1 noted the benefits of ensuring doctor rotations to local communities: "If, for example, an eye doctor comes on Mondays and a surgeon comes on Tuesdays, wouldn't people in rural areas be happier with that?"

4-3-3 Positive marketing and Japan branding

Positive marketing and leveraging Japan's strong brand image can foster social acceptance. The involvement of well-established Japanese airlines like ANA and JAL can enhance customer confidence. An operator (OP2) stated, "The general customers are more likely to feel safe and secure if it is operated by ANA or JAL." This sentiment is reinforced by partnerships such as Joby's collaboration with Toyota, which emphasizes quality and safety.

4-3-4 Economic impact

UAM can promote regional revitalization and economic growth by creating employment opportunities and attracting new residents. Trading companies believe that air mobility could provide tangible benefits to society. TC2 remarked, "Using this kind of air mobility to support residents in remote islands with poor access... will be a tangible benefit to society."

4-4 Key factors influencing the successful creation of an ecosystem and market penetration strategy for UAM service providers in Japan

4-4-1 Ecosystems in a Japanese environment

The definition of the UAM ecosystem has been given in paragraph 2.2. Due to the availability of resources on the different solutions such as Volocity, VoloIQ, and Voloport, the ecosystem conceived by Volocopter has been taken as a reference during the interviews. Stakeholders concurred on how difficult it would be for one company to uniformly implement an ecosystem in Japan. The manager of a major Japanese company (INS1) believes that presenting a packaged, integrated ecosystem model would be beneficial for promoting new entry into the market.

A University Professor (RI2) noted, "It is natural that a business ecosystem is necessary, and this figure is not sufficient as it does not yet include many stakeholders." The CEO of a Japanese operator sees potential business development: "If we propose it to Volocopter, we can handle the ports, operations, and maintenance... there is potential for us to grow."

4-4-2 Market entry strategies

Stakeholders link Volocopter's ecosystem vision to a first-to-market strategy. Being the first to market may require a company to do everything themselves, from manufacturing to service delivery. An OEM strategy manager (OEM5) noted, "If you want to market yourself as the first to market, then you must do everything." However, as the market develops, companies can specialize and focus on their core competencies.

The failure of foreign companies like Uber in Japan was frequently mentioned. The manager of a trading company (TC2) explained, "When Uber came to Japan, they didn't do any groundwork or collaborate with the taxi industry... I think it might be difficult for this (UAM) to really take hold in Japan." An OEM director (OEM2) noted, "Uber couldn't enter Japan... they are doing dispatch apps with Japan Taxi." Successful entry requires understanding and adapting to Japanese market specificities.

4-4-3 Business development, established companies vs new entrants competition & Japanese market

Interviews revealed that the UAM market will not reshuffle the existing market but will expand it. An academic professor (RI3) noted, "The market itself will expand... helicopter operating companies may operate UAM." A new entrant OEM manager (OEM4) sees potential for new entrants due to lower pilot training costs: "If the cost of training pilots becomes much lower with flying cars, there will be room for many companies to enter."

Trading companies will play a significant role by potentially acquiring established helicopter operators and planning to operate vertiports. An academic professor (RI2) indicated, "Trading companies can gather funds and acquire helicopter companies." Development banks also observe this trend: "Sojitz recently acquired Okayama Aviation."

4-4-4 Vertiport considerations in Japan

Doubts have been raised regarding the potential monopoly of one company over the development of vertiports. A major airlines manager (OP2) stated, "It would be better to have them as public facilities, where various types of aircraft can land." An academic professor (RI1) noted, "If the government is responsible for the initial development, the system will be available to anyone." A manager from an airport facility building company believes the government will establish rules for public facilities but will decide for places integrated into current airports.

This same manager explains that there will be three different types of ports - small, medium, and large. "For large-scale facilities, build at airports or ports; for mid-sized ports, build in tourist destinations; for small-scale facilities, build on rooftops of buildings or in small towns."

4-5 Summary of use cases with potential in Japan

During the interviews, the participants identified the Seto Inland Area as a promising region for UAM implementation. A major Japanese airline director (OP2) indicated potential in regions that could not accommodate helicopters in the past: "In the past, Japan had a commuter helicopter business in areas like the Seto Inland Sea... it's a feeling that something new will be born."

A trading company manager (TC1) remarked, "It's hard to imagine many flying vehicles over Tokyo right away. Securing routes in places like the Seto Inland Sea might lead to a sense of security." The director of an investment bank (BK1) concurred, "The Seto Inland Sea is definitely the right choice." Using UAM for tourism is seen as a viable initial application, eventually expanding to emergency transport and other uses.

The METI and the Development Bank of Japan have detailed potential use cases in the Setouchi area, including maps and tables comparing distances and access times by cars, trains, and UAM.

These findings underscore the importance of a collaborative approach involving government, industry, and the public to overcome challenges and leverage opportunities for successful UAM implementation in Japan.

5. Discussion

5-1 Summary of findings

5-1-1 First research question

The aim of this research was to explore the different stakeholder perceptions of social acceptance in Japan and identify the associated challenges and opportunities. The research identified several key themes related to stakeholder perceptions of social acceptance and effective strategies for promoting buy-in and fostering a sense of collective responsibility. These themes include stakeholders' concerns regarding the exclusive and inaccessible nature of EVTOL, as well as potential issues with demand, profitability, cost, regulatory hurdles, battery, and technology limitations.

Additionally, the unique characteristics of Japanese society and industry, such as the emphasis on perfectionism and risk-aversion, were identified as relevant factors. To foster social acceptance, several effective opportunities that stakeholders in the UAM industry have been identified, such as following government or municipal leadership, utilizing positive marketing and Japan branding, offering community-wide benefits, and encouraging Japanese company contributions.

5-1-2 Second research question

The findings of this study on the key strategic considerations for UAM stakeholders seeking to integrate with Japan's existing transportation network reveal that stakeholders are not inclined to accept a monopoly by a single company within the ecosystem. This is due to the economic challenges posed by such a structure in Japan. Instead, the "First to Market" strategy encourages new entrants to develop and promote their ecosystems, while recognizing that, eventually, tasks will need to be divided among all stakeholders.

Moreover, the study highlighted that Japan is a unique market. Companies like Uber have failed to establish themselves here, not due to lobbying by existing business entities, but because of Japan's distinct regulatory, cultural, and business landscape. For instance, Japan's market places a strong emphasis on long-term partnerships, compliance with highly specific regulations, and societal alignment with new technologies. Foreign companies often struggle to adapt to these factors. This underscores the importance of paying close attention to the specific rules and cultural nuances of the Japanese market for effective market entry.

While the perception that there will be no reshuffling of the traditional aerospace industry in Japan was noted, the study suggests that this may not be entirely accurate. Instead of a complete reshuffling, gradual shifts are likely, particularly in the role of trading companies. These companies, traditionally focused on facilitating business transactions, may pivot towards operational roles in the UAM ecosystem, such as managing vertiports or directly engaging in UAM operations.

Thus, companies aiming to enter the UAM industry in Japan must remain flexible and prepare for potential shifts in the industry landscape. Understanding and adapting to Japan's unique market dynamics will be essential for long-term success.

5-2 Discussion and result interpretation

The Technology Acceptance Model for Disruptive Transport Technologies, adapted from the original TAM [26], and the Automation Acceptance Model (AAM) [27] provide useful frameworks for understanding the factors that influence the adoption and use of urban air mobility (UAM). These models include four key components: perceived usefulness, perceived ease of use, social influence, and facilitating conditions. In this discussion chapter, these components of the UAM framework and ecosystem will be used to analyze the findings.

5-2-1 The framework

Social fairness / social acceptance

The need for social fairness has been addressed by most stakeholders. This point aligns with current research, which states the need to scale the UAM market to ensure social fairness. Addressing challenges such as regulatory frameworks, safety and infrastructure standards, and community acceptance is critical for the growth and success of the UAM market in Japan. Overall, addressing the perception of flying vehicles as exclusive and inaccessible is essential for the growth and success of the UAM market in Japan.

Demand, profitability, and cost

The concern of not finding enough customers willing to pay for UAM services is a critical issue highlighted by the academic expert (RI4). The economic viability of UAM operations is highly dependent on their scalability. While Japan may not have enough traffic congestion to justify UAM as a solution to traffic problems, other potential use cases exist in rural and island regions, as well as for tourism. Progress in remote operation, automation, and battery technology could make UAM business models more sustainable and profitable in Japan by the 2030s.

Regulations

The regulation of UAM is a significant challenge for its adoption in Japan. The Japan Civil Aviation Bureau (JCAB) has eased regulations for flight testing and demo flights of UAM vehicles, allowing some OEMs to conduct successful demo flights. However, strict regulations regarding small aircraft and the need for a nuanced understanding of regulatory challenges remain obstacles. Continued efforts to align Japan's regulations with international standards are necessary.

Battery and technology limitations

The findings indicate that stakeholders, particularly OEMs, view battery technology as a major challenge for Urban Air Mobility (UAM) and emphasize the need for further investigation into its real impact on sustainability. This aligns with the current state of research, which highlights battery technology as a critical barrier to UAM implementation globally [13]. Despite recent breakthroughs, batteries still have significantly lower energy density compared to fossil fuel propulsion, impacting the vehicle's range, payload capacity, and overall performance.

Moreover, achieving sustainable mobility necessitates a comprehensive approach to the battery life cycle, including environmental impact and recycling. As noted by [14], the demand for batteries is projected to rise significantly, underscoring the importance of ensuring that UAM batteries are sustainable and circular—capable of being reused, repurposed, and recycled. The reduction targets for aircraft CO2 emissions are ambitious, with the International Civil Aviation Organization (ICAO) aiming for zero net CO2 emissions by 2050 [28]. This goal will similarly drive higher sustainability standards for UAM. Addressing these challenges requires ongoing research and innovation to make UAM a viable and environmentally friendly transportation option.

Japanese society and industry particularities

The findings highlight Japan's cultural emphasis on zero risk and perfection (TC2). Governmental agencies are motivated to link UAM development with the automotive sector, but the established rail industry may hinder UAM progress (OEM1).

The Japanese automotive industry, lagging in electrification, sees UAM as an opportunity for innovation. "Japan went with hybrids, while Europe and the United States went straight to EVs. Japan was left behind in terms of electrification, and the automotive industry feels a sense of crisis." Consequently, the Ministry of Economy, Trade and Industry supports UAM development (RI3). The term "flying car" (Sora Tobu Kuruma) resonates with Japan's automotive sector and has been popularized through media [29], although the public often views EVTOLs as "manned drones" [30] .

Japan's zero-risk culture, stemming from the Fukushima nuclear incident, can lead to caution in adopting new technologies (TC2,[31]). However, drones are already flying over homes, indicating progress in risk management (RI2). Lessons from the nuclear industry underscore the importance of proper risk evaluation for UAM.

5-2-2 The ecosystem

Government's roadmap

Findings indicate that Japan's UAM infrastructure development relies heavily on government leadership, local government support, and public-private partnerships. The Japanese government, particularly METI, has been proactive, organizing eight seminars since 2018 to advance UAM [22]. The METI roadmap, updated regularly, outlines a comprehensive plan for UAM development in three phases: initial (2018-2020), demonstration (2021-2025), and practical use (2026-2030).

The roadmap emphasizes UAM's potential to reduce urban congestion, improve disaster response, and enhance remote area accessibility. It sets a vision for "a society where people can move freely and safely in the air," focusing on regulatory reforms, infrastructure, technology development, and international cooperation. Key measures include establishing a legal framework, developing vertiports, conducting vehicle tests, and harmonizing global regulations.

Japan's approach, more comprehensive than EASA and FAA roadmaps, aims for a holistic UAM implementation, integrating infrastructure and technology advancements with regulatory and safety considerations. This broader scope suggests a more effective implementation process.

RI2 notes that despite limited venture capital, the government fosters corporate investment through its roadmap. The upcoming Universal Exhibition could further boost UAM visibility, attracting public interest, investment, and talent to Japan.

Market entry strategies

The timing of entry and the competitive landscape are crucial for companies entering the UAM market in Japan. The first-to-market strategy may require companies to do everything themselves in the early stages. However, as the market develops, specialization and collaboration become more feasible. Building local ecosystems and collaborating with local partners is essential for navigating Japan's unique market conditions.

Stakeholders landscape

The UAM market in Japan is a ground for competition between new entrants and established players. Major Japanese Aerospace OEMs are involved in UAM development but show less interest in developing their own EVTOLs, creating opportunities for new and foreign entrants [32]. Companies like Denso and Honeywell are expected to play significant roles in the UAM supply chain, developing motors and inverters through a long-term partnership [23].

Operators, such as JAL and ANA, are crucial due to safety concerns in Japanese culture. Smaller helicopter operators face competition from trading companies, which are new to the UAM market but established in traditional aerospace. Companies like Sojitz have started acquiring operators, indicating a strategic move into the UAM sector [33].

Foreign companies entering the Japanese UAM market should consider the competition landscape, partnerships with operators, and collaboration opportunities with battery and motor companies. UAM holds potential advantages for communities, addressing regional social issues, stimulating economic progress, and promoting growth [6]. UAM can aid during natural disasters, improve access to remote areas and medical facilities, and enhance tourism and business opportunities. Local communities play a vital role in managing UAM operations, especially in urban areas, with potential synergies with the drone industry, exemplified by TrueBizon's financial compensation system for flyovers [34].

Vertiport considerations

The development of vertiports should be public facilities accessible to various companies rather than being monopolized by one company. The involvement of the government in establishing rules for public facilities is crucial. Different types of ports (large, medium, and small) should be developed to meet the needs of various regions and use cases.

5-3 Limitation of the study & suggestions for future research

The study's findings are based on the perspectives of industry specialists, which could result in potential biases. As the interviewees were selected from organizations directly involved in the UAM ecosystem, their views may reflect an industry-centric outlook and may not fully capture concerns or skepticism from the general public or other independent stakeholders.

To mitigate this limitation, future research could include a broader range of participants, such as members of the general public, non-governmental organizations, and environmental advocates. A supplementary public survey could provide additional insights into social acceptance and concerns about UAM. Furthermore, clarification and communication of the definition of "flying car" may be necessary to enhance understanding and acceptance. A comparative analysis between Europe and Japan on social acceptance for UAM could also offer further valuable perspectives.

6. Concluding summary

This research focused on the potential of UAM in Japan, highlighting opportunities and challenges. Recommendations for addressing social fairness, safety, and regulatory issues include promoting community-wide benefits, positive marketing, and encouraging Japanese industry contributions. Collaboration with Japanese government agencies and trading companies is crucial for successful UAM implementation.

Recommendations:

1. Social Fairness: Address perceptions of exclusivity and inaccessibility by promoting community-wide benefits and positive marketing.
2. Technological and Safety Aspects: Communicate these aspects through public demonstrations and educational initiatives.
3. Japanese Industry Contribution: Develop a domestic supply chain for UAM components and involve Japanese industry in infrastructure development.
4. Market Entry: Partner with Japanese trading companies and establish strong relationships with municipalities.
5. Use Cases: Analyze the potential for UAM development in the Seto Inland area.

By following these recommendations and working collaboratively, UAM could become a reality in Japan, providing a new mode of transportation that benefits communities throughout the country.

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固定翼 UAV の短距離着陸を目的とした瞬時降下率最大化による減速旋回降下技術の研究

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近年無人航空機の利用が進む中，固定翼 UAV は高速・長距離飛行が可能であるため様々な分野での活用が検討されている [1, 2]。しかし，高速飛行を行う固定翼 UAV は着陸距離が増大する。この問題に対して本研究では通常の直線経路に沿って飛行速度一定で降下するグライドスロープに対して，複数回旋回飛行しながら減速と降下をする「減速旋回降下技術」を提案し，水平距離を短縮するとともにタッチダウン時の飛行速度を減少させることによるロールアウト距離の短縮を目指す。提案技術は高精度に旋回経路を追従する技術の上に，速度は一定の加速度で減速，飛行状態より計算したその瞬間でとれる最大の降下率で降下させる技術より構成される。本稿では，提案技術の 6 自由度シミュレーション結果及び，「高精度旋回経路追従技術」について飛行試験により検証した結果を報告する。

Keywords: UAV，旋回，減速，降下，着陸，シミュレーション，飛行試験

Study on Deceleration and Turning Descent Technology by Maximizing Instantaneous Descent Rate for Short-range Landings of Fixed-wing UAVs

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As the use of unmanned aerial vehicles has advanced in recent years, fixed-wing UAVs have been developed for use in various fields for their high-speed and long-distance flight capabilities [1, 2]. However, fixed-wing UAVs that fly at high speeds require a long landing distance. To address this issue, this study proposes a deceleration and descent technology that incorporates multiple turning maneuvers as opposed to the conventional glide slopes that allow for descent at a constant flight speed along a normal straight-line path. This approach can shorten the horizontal and roll-out distances by decreasing flight speed at touchdown. The proposed technology combines highly accurate turn path tracking control with the generation of commands for speed deceleration and the maximum achievable descent rate based on real-time flight status. Using the proposed technology, 6-DOF simulations are carried out to confirm its validity, followed by flight experiments to evaluate its performance.

Keywords: UAV, Turning, Deceleration, Landing, Descent, Flight simulation, Flight verification

Nomenclature

a : Acceleration
$C_{L\alpha}$: Lift curve slope
D : Drag force
g : Gravitational acceleration
h_a : Initial altitude
h_f : Flare initiation altitude
m : Total weight of the airplane
R : Turning radius
S : Wing area
T_{min} : Minimum thrust of the UAV
t_f : Flare start time
V_a : Initial flight velocity
V_f : Flare initiation flight velocity
α : Angle of attack
ρ : Air density
τ : Flare time constant
ϕ : Roll angle
ψ : Nose azimuth angle

1. Introduction

In recent years, the use of unmanned aerial vehicles (UAVs) has advanced, enabling applications such as services for monitoring agricultural land, surveying disaster-stricken areas, and transporting goods, and research and development exploring future possibilities in these areas is ongoing [3]. In particular, the use of fixed-wing UAVs is more advantageous than rotary-wing multicopters in the field of logistics and in disaster damage assessment due to their superior speed and longer flight range. However, fixed-wing UAVs that fly at high speeds require a long landing distance. This makes it impossible to land in forested or urban areas with high obstacles in the vicinity of the landing site. To address this problem, this study aims to reduce the horizontal distance required for landing by using both highly accurate turn path tracking and deceleration with turning descent technology.

Usually, in glide slope landings, airplanes follow a straight descent path at a constant speed before transitioning to the flare phase, in which the descent rate is reduced inversely proportional to its altitude, resulting in a small impact at touchdown. In conventional short-range landing technology, airplanes increase their angle of descent (glide slope angle) in the glide slope phase [4, 5]. In contrast, the proposed deceleration and turning descent technology enables airplanes to decelerate and descend while performing multiple turns along a predetermined circular trajectory. This method shortens the horizontal distance required for landing while simultaneously reducing flight speed at the time of touchdown. This leads to a shorter rollout distance, which in turn reduces the required runway distance.

As this technology is applied from the start of the landing phase to just before the flare phase, it is important to minimize the deviation from the target turning path. Therefore, a flight control system that enables continuous and highly accurate turning along a predetermined circular path is required. There are many papers on turning technology, including a study on saving space in half-circle turns [7] and a study on following complex paths with gentle curves [8]. However, no prior research has focused on achieving continuous turning along a predetermined circular path. To address this gap, the authors utilize their previously reported highly accurate turn path tracking technology for continuous turning to reduce the turning path deviation [9].

Secondly, in previous studies on deceleration and turning descent technology [6], the rate of descent during deceleration and turning descent was regarded as constant to simplify calculations. However, this assumption led to prolonged flight times from the start of landing to touchdown. Therefore, in this paper, the maximum instantaneous descent rate that can be realized is calculated in real time by using flight status data.

Finally, the present paper describes the results of a 6-DOF simulation conducted to validate the proposed deceleration and turning descent technology, followed by flight verification experiments using a small fixed-wing UAV to assess the accuracy of the turn path tracking technology.

2. Proposal of deceleration and turning descent technology

The main objective of the proposed deceleration and turning descent technology is to reduce the horizontal distance for landing, which will enable fixed-wing UAVs to land in small spaces where only multicopters would typically be able to land. The details of the landing flow are described below.

The landing profile using the deceleration and turning descent technology consists of four flight phases. The first phase is the horizontal turning phase. The purpose of this phase is to eliminate the initial path errors before entering the next deceleration and turning descent phase, so as to realize an accurate turning path. The second phase is the deceleration and turning descent phase. In this phase, the UAV descends by executing multiple turns along a circular trajectory with a constant turning radius while simultaneously decelerating its speed. The descent occurs at the maximum rate of descent and decelerates at a constant rate of acceleration. In the third and fourth phases, the UAV goes through the transition and flare phases, respectively, leading to touchdown. The transition phase is responsible for positioning the UAV on the runway and reducing the deep roll angle induced by turning to zero in preparation for the flare phase.

Deceleration and descent continue during the transition phase. Fig.1 shows an image of the landing flow described above.

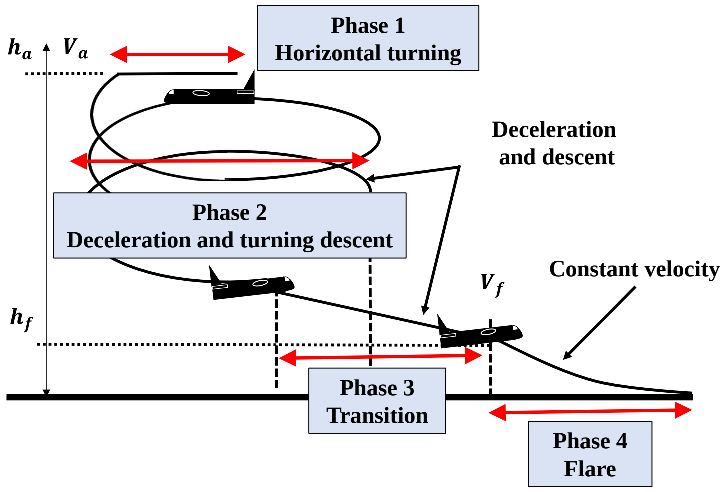

Fig.1 Landing flow of deceleration and turning descent technology.

3. Derivation of target values

For manned airplane, risky flight maneuvers such as deep rolls and low-speed flight close to stall conditions are generally avoided in consideration of safety. However, since this technology is specifically designed for UAVs, it is possible to set target values that make the best use of UAV performance.

In applying the deceleration and turning descent technology to UAVs, target values are set for three parameters: flight speed, turning radius, and descent rate. The policies and derivation methods for each of these parameters are described below.

3-1 Minimum flight speed

Flight speed is an important parameter that determines the distance the UAV will run after its touchdown.

This technology reduces the required runway distance by minimizing the flight speed at touchdown after deceleration during descent. The minimum flight speed at touchdown is determined up to and just before the stall limits of the UAV.

In general, the stall speed V_{stall} is derived using the stall angle of attack α_{stall}, which is a characteristic of the UAV's performance. Eq. (1) is a transformation of the equation for the longitudinal force acting on the UAV and is used to derive the stall speed V_{stall}.

$$V_{stall} = \sqrt{\frac{2mg}{\rho S C_{L\alpha} \alpha_{stall}}} \tag{1}$$

For safety, the minimum flight speed is defined as the stall speed V_{stall} derived in Eq. (1) with a margin of 30%, and this is set as the flight speed at the start of the flare phase V_f (Eq. (2)). Since the flight speed is kept constant during the flare phase, which is without deceleration, the minimum flight speed can be maintained for touchdown.

$$V_f = 1.3 V_{stall} \tag{2}$$

3-2　Minimum turning radius

The horizontal distance covered during deceleration and turning descent depends only on the turning radius, so minimizing the turning radius will result in a shorter horizontal distance. The minimum turning radius can be derived structurally by using the load carrying capacity of the target UAV [10]. However, in this case, the minimum turning radius R_{min} is derived from the maximum roll angle ϕ_{max} of the UAV.

First, the maximum roll angle ϕ_{max} of the UAV is derived. Eq. (3) is a transformation of the equation for the longitudinal force balance during turning, and is used to determine the maximum roll angle ϕ_{max}.

$$\phi_{max} = \cos^{-1}\left(\frac{2mg}{\rho S {V_f}^2 C_{L\alpha} \alpha_{stall}}\right) \tag{3}$$

Next, the minimum turning radius R_{min} is calculated by using Eq. (4), which is derived from the equilibrium equations for longitudinal and lateral forces during the turning. Substituting the maximum roll angle ϕ_{max} derived in Eq. (3) into Eq. (4), the minimum turning radius R_{min} can be derived.

$$R_{min} = \frac{V^2}{\tan(\phi_{max}) g} \tag{4}$$

3-3　Maximum rate of descent

The descent rate determines the flight time required for landing. Since the proposed technology reduces the UAV's speed greatly, the descent rate must be maximized to compensate for the potential increase in flight time. We proposed the following procedure to determine the maximum rate of descent.

First, by using the relationship between the forces in the direction of flight, the maximum rate of descent can be derived as shown in Eq. (5) with the flight speed as a variable. Here, the angle of attack used to calculate the drag force D in Eq. (5) is derived from the lateral equilibrium equation in order to maintain stability during turning. T_{min} is the minimum thrust of the UAV.

$$dh/_{dt} = V \cdot \sin^{-1} \frac{D - T_{min}}{mg} \tag{5}$$

Next, the descent altitude can be calculated by integrating the rate of descent up to the flare start time, as shown in Eq. (6). Here h_a is the initial altitude of the landing and h_f is the initiation altitude of the flare. In general, the flare initiation altitude is derived using Eq. (7).

$$\int_0^{t_f} {dh}/{dt}(V) \quad dt = h_a - h_f \tag{6}$$

$$h_f = {dh}/{dt} \cdot \tau \tag{7}$$

Finally, Eq. (8) is defined to derive the flight speed using the acceleration a during deceleration and turning descent.

$$V(t) = at + V_a \tag{8}$$

Substituting Eq. (5) and Eq. (8) into Eq. (6) and solving the definite integral, we obtain the flight time required for deceleration and descent (flare start time t_f), the flight acceleration a, and maximum rate of descent.

4. Target UAV and path

4-1 Target UAV

The target UAV for this study is a low-wing glow fuel-powered model UAV, as shown in **Fig.2**. **Table 1** lists the UAV specifications.

Fig.2 Photograph of UAV.

Table 1 UAV specifications.

Total weight	m	5.5 kg
Wing area	S	0.65 m^2
Aspect ratio	AR	6.54
Wing efficiency	e	0.6
Lift curve slope	$C_{L\alpha}$	4.355 1/rad
Parasite drag coefficient	C_{D0}	−0.0485
Minimum thrust	T_{min}	3 N

4-2 Derived target path

Using UAV specifications listed in **Table 1** and initial conditions from **Table 2**, the target values are calculated following the procedures described in Section 3.

Table 2 Initial conditions.

Initial altitude	h_0	100 m
Initial flight velocity	V_0	25 m/s
Transition phase duration		5 s
Flare time constant	τ	2.5 s

The computed target values are shown in Fig.3 together with the landing profile. Given the runway distance limitations for the flight verification experiment, the UAV initiates its turn from the opposite side of the landing direction, and after turning n.5 times (n = real number), it aligns its nose with the landing direction on the runway and lands.

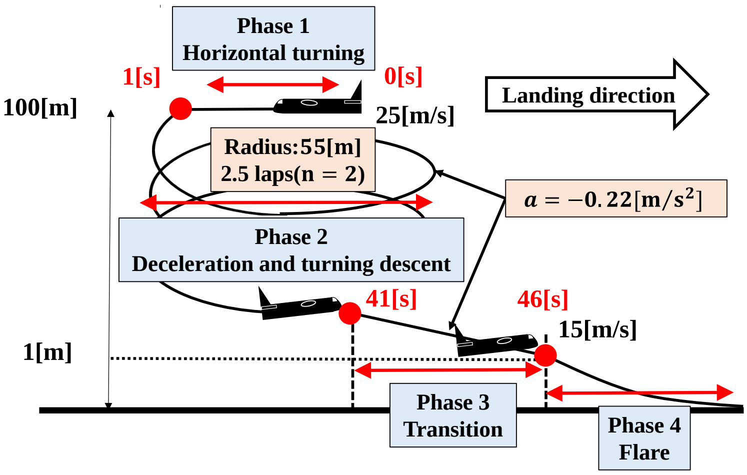

Fig.3 Derived target values and landing profile.

The minimum turning radius of the target UAV was calculated to be 55 m. The UAV performs a 2.5-lap deceleration and turning descent trajectory with a turning radius of 55 m. After maintaining a horizontal turning phase for 1 second, it transitions into the deceleration and turning descent phase, followed by a 5-second transition phase, reaching the flare phase at 46 seconds. During the transition from the deceleration phase to the flare phase, the UAV experiences an acceleration of −0.2 m/s^2. At the start of the flare phase, the UAV decelerates to 15 m/s, its minimum flight speed, and descends from an altitude of 100 m to 1 m. The time histories of the maximum rate of descent and the altitude are shown in Figs.4 and 5, respectively. The time history of the maximum rate of descent is shown in Fig.4. Additionally, Fig.5 shows the time history of the altitude calculated by the maximum rate of descent. The time history of the altitude is input as a command to the simulation to be performed later.

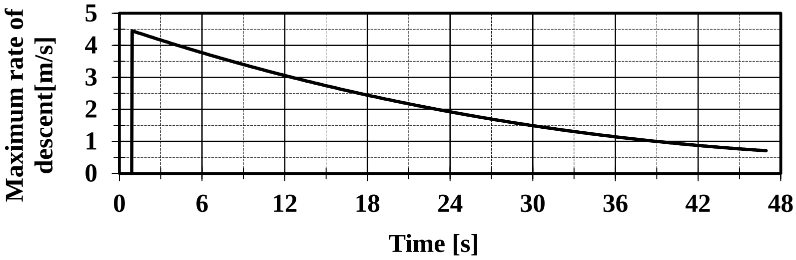

Fig.4 Time history of the maximum rate of descent.

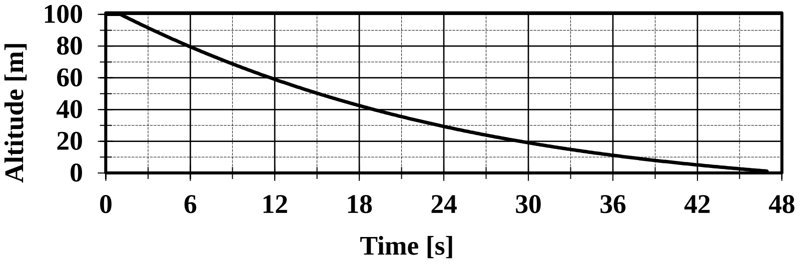

Fig.5 Time history of altitude.

5. Control systems

In order to realize the proposed deceleration and turning descent flight, the following three systems were designed: speed control, altitude control, and turning path tracking control.

(a) Speed control system

The airspeed is controlled by the throttle. Airspeed is measured using a Pitot tube mounted on the UAV, and the airspeed command is given to decelerate the airspeed at a constant rate, as calculated in Section 4. Deviations from the command are processed through a PID controller to generate the engine throttle command.

(b) Altitude control system

The altitude is controlled by the pitch angle. Sensors installed on the airplane measure the altitude, and the time history of the altitude calculated from the maximum rate of descent shown in **Fig.5** is used as input for the descent command. Deviations from the command are processed through a PID controller to generate the pitch angle command.

(c) Turning path tracking control system

This control system is indispensable to realize the proposed technology. It enables the UAV to track the target turning path by focusing on the turning radius deviation and nose azimuth angle. The azimuth command ψ_{cmd} generated from the turning radius deviation and the ideal azimuth angle $\psi_{\tan}$ calculated from the current position and the turning center of the UAV are added together and input to the nose azimuth angle control system. Then, from the deviation between this added command and the current nose azimuth angle ψ, a roll angle command ϕ_{cmd} is generated and input to the roll angle control system (**Fig.6**).

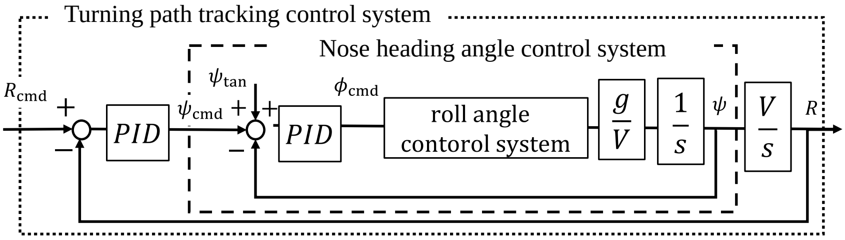

Fig.6 Turning path tracking control system.

6. Simulation

6-DOF simulations using Matlab/Simulink were performed to confirm the effectiveness of the proposed technology.

6-1 Simulation conditions

The simulation consists of a 50-second linear path-following controlled flight at a speed of 25 m/s, followed by the landing profile shown in **Fig.3**. Initial conditions are summarized in **Table 2**. Sensor noise, as observed in actual flight experiments, was added in the simulation, with standard deviations as summarized in **Table 3**. Also, the feedback rate for simulation is 40 ms.

Table 3 Standard deviation of sensor noise.

Attitude angle	0.5 deg.
X, Y direction	3 m
Altitude	0.2 m
Velocity	0.17 m/s

6-2 Target performance

For the simulation, target performance parameters were defined for touchdown. **Table 4** lists the lateral position deviation at touchdown, determined from the runway width of 6 m, and the rate of descent at touchdown, based on the target UAV's leg structure.

Table 4 Target performance at touchdown.

Lateral position deviation	±3 m
Rate of descent	1 m/s

6-3 Simulation results

Fig.7 shows the flight path, velocity, altitude, and attitude angles obtained from the simulations. The time histories show results after 50 seconds into the horizontal turning phase. **Fig.7(a)** and **(b)** show the flight trajectories, demonstrating that the UAV followed the target path for a turning descent of 2.5 laps. **Fig.7(c)** and **(d)** respectively show the time histories of velocity and altitude. It can be seen that both are following the command, decelerating and descending as expected. **Fig.7(e)** shows the time history of the turning radius. At the start of the turn, the radius overshoots due to a delay in the control system, but eventually converges to the command. **Fig.7(f)** and **(g)** show the pitch and roll angles, respectively. It can be seen that both angles are following the command.

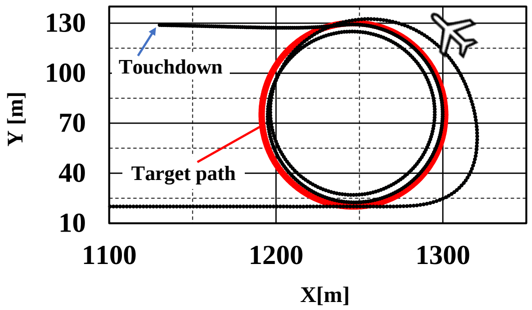

Fig.7(a) Flight path (X-Y).

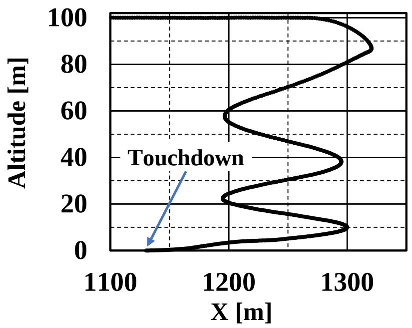

Fig.7(b) Flight path (X-Altitude).

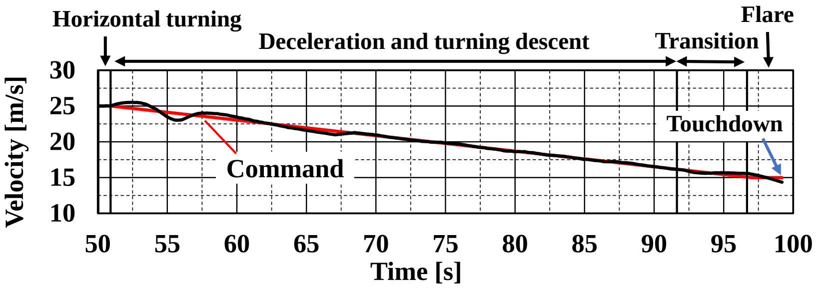

Fig.7(c)　Time history of velocity.

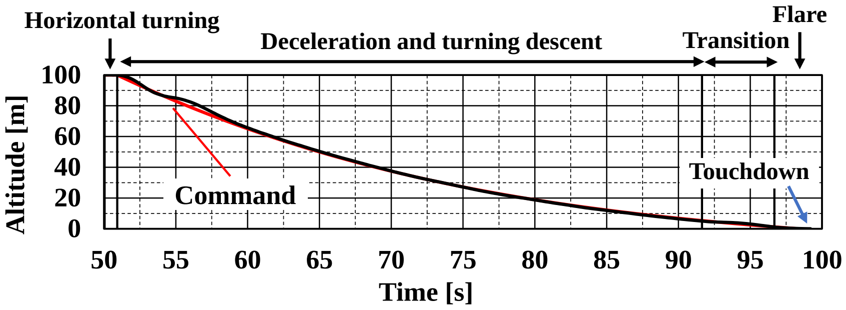

Fig.7(d)　Time history of altitude.

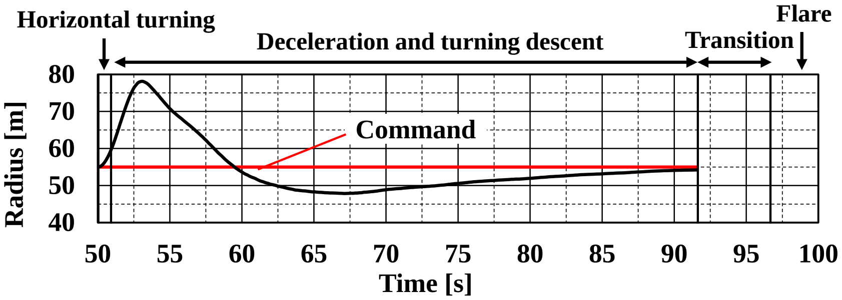

Fig.7(e)　Time history of turning radius.

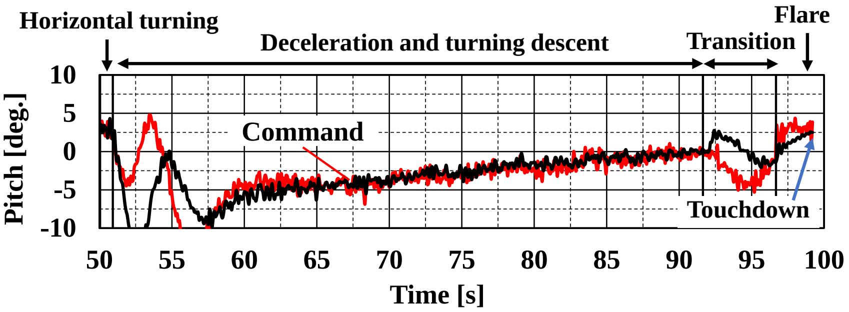

Fig.7(f)　Time history of pitch angle.

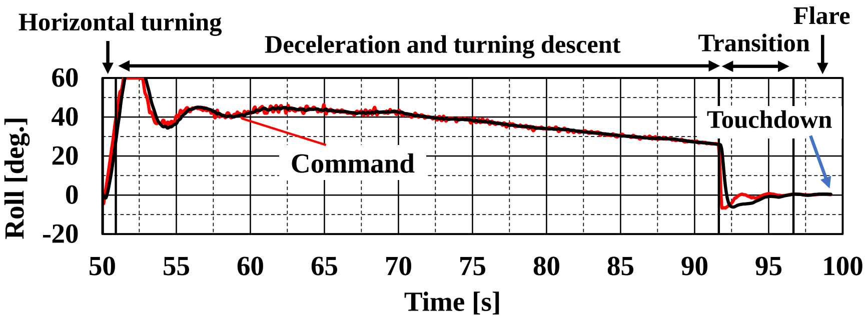

Fig.7(g)　Time history of roll angle.

Next, the performance at touchdown is summarized in **Table 5**. These results were confirmed to be within the target performance parameters.

Table 5 Simulated performance at touchdown.

Lateral position deviation	1.1 m
Rate of descent	0.12 m/s

6-4 Discussion of results

The total landing distance is evaluated for the simulation results using this technology compared to the conventional technology [4]. The landing distance is defined as the horizontal linear distance covered by the plane as it descends from an altitude of 100 m to touchdown. However, for the distance from touchdown to stop (roll-out distance L_o), an approximate formula Eq. (9) [11] is used.

$$L_o = \frac{1}{2g}\frac{V^2}{D/W} \tag{9}$$

By applying the conventional technology to the target UAV in this study, the maximum glide slope angle is calculated to be 15 deg. The UAV descends at a constant flight speed, and after a flare phase, it touches down at a horizontal distance of 530 m. The UAV then glides over the runway for a distance of 30 m, stopping at 560 m.

In contrast, in the simulation using the proposed technology, the UAV touches down at a horizontal distance of 190 m. Then, the UAV stops after a distance of 10 m, which is much shorter than the runway distance required by the conventional technology, because the speed of the UAV is reduced to 15 m/s. Therefore, the total landing distance is reduced to 200 m, representing a 64% reduction in horizontal distance.

7. Flight verification

To validate the proposed technology, flight verification experiments were conducted in stages using the fixed-wing UAV shown in **Fig.2**. The flight experiment was carried out at the Shiraoi Gliding Port in Hokkaido, Japan. The weather on the experiment day was favorable, with a temperature of about 15 degrees Celsius and a steady wind of 2 to 3 m/s. The feedback rate was 40 ms, the same as in the simulations. First, the continuous level turning flight experiment was carried out, which involves a highly accurate turn path tracking technology. For the target UAV, the minimum turning radius was set to 55 m. The shorter the turning radius is, the bigger the roll angle during the turn. In the flight experiment conducted in a previous study [9], the altitude of the UAV dropped by almost 7 m for a turning radius of 70 m.

Therefore, in the present paper, flight experiments were carried out sequentially with a turning radius of 85 m, 70 m, and 55 m, in that order, and the effect of changes in the turning radius on the altitude were investigated.

In all cases, the UAV was set to fly 3.5 laps of continuous circles, and was controlled to maintain a constant altitude at the beginning of the experiment and a constant airspeed of 25 m/s.

7-1 Target performance for flight verification experiments

The purpose of this test is to confirm the convergence of the highly accurate turn path tracking technology applied to the deceleration and turning descent phase. Therefore, the turning radius deviation was set and evaluated as the target performance after convergence. The target performance of the converged deviation was set within 9 m, which takes into account the positional error of 3 m measured by the sensor and control errors. For the experiment, only the average deviation after the second lap was evaluated, because the first lap of the continuous turning expands the turning path due to the delayed response of the roll.

7-2 Results of flight verification experiments

The flight paths and time histories of the turning radii of 85 m, 70 m, and 55 m are shown in **Figs.8** to **10**, respectively. The black line in the flight path diagram represents the circular path of the target.

Fig.8(a) Fight path (85 m).

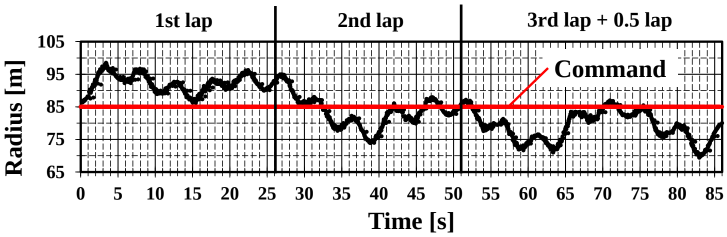

Fig.8(b) Time history of turning radius (85 m).

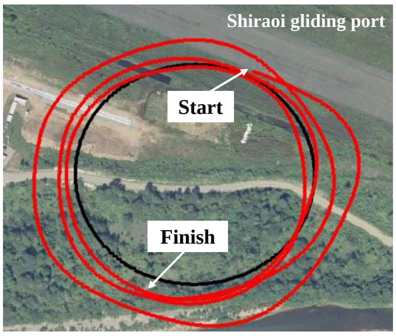

Fig.9(a) Fight path (70 m).

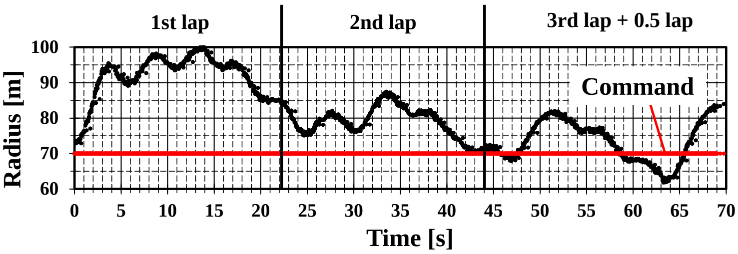

Fig.9(b) Time history of turning radius (70 m).

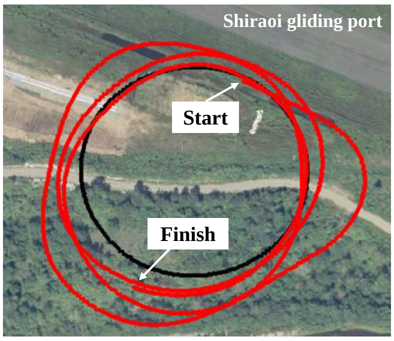

Fig.10(a) Fight path (55 m).

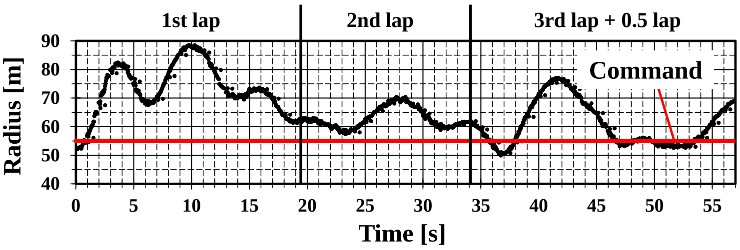

Fig.10(b) Time history of turning radius (55 m).

All patterns show continuous turning along a path that is generally in line with the target path. However, compared to the time history of the turning radius in the simulation (**Fig.7(e)**), in the actual flight experiment, the turning radius is oscillating. This is considered to be due to the 2 to 3 m/s wind disturbance present in the flight verification experiment environment. The simulations described in Section 6 did not take wind disturbance into account, so no oscillations were observed. On the other hand, in a previous study [9], a horizontal continuous turning simulation under the condition of 3 m/s wind disturbance was conducted that found oscillations of about 3.6 m for a command with a turning radius of 70 m. Therefore, the oscillations observed in the turning radius in this experiment are judged to be acceptable.

The experiments were conducted multiple times to confirm the reproducibility of the test, and it was found that with wind disturbance of more than 5 m/s, the turning radius showed greater oscillations and tended to diverge.

Next, we consider the convergence. As expected for all patterns, the first lap was affected by the delay of the control system and the response delay of the roll, and the radius deviation tended to increase. The average deviation excluding the first lap is summarized in **Table 6**. In all cases, the radius deviation converged to within 9 m of the target performance. In addition, it was found that even with a minimum turning radius of 55 m for the target UAV, the target performance could be satisfied and continuous turning was possible. From these results, the validity of the highly accurate turn path tracking technology was confirmed, and it became clear that the proposed technology can actually be applied to the deceleration and turning descent phase.

Table 6 Convergence values for each turning radius.

Target turning radius	Average deviation excluding the first lap
85 m	5.2 m
70 m	7.0 m
55 m	7.2 m

Next, the effect of varying turning radius on altitude is discussed. **Table 7** summarizes the deviation from the altitude command after 3.5 laps for each turning radius we investigated. As initially predicted, it became clear that reducing the turning radius to 55 m resulted in an increase in the altitude deviation. However, the same PID parameters of the altitude control system are applied for all turning radii. It is expected that the increase in the altitude deviation can be mitigated by redesigning the controller parameters to improve the response when the UAV must execute turns with a smaller radius.

Table 7 Deviation from the altitude command after 3.5 laps for each turning radius.

Target turning radius	Deviation from the altitude command after 3.5 laps
85 m	−5.6 m
70 m	−5.4 m
55 m	−7.2 m

8. Conclusion

In this paper, a new UAV landing technology that incorporates a deceleration and turning descent during the glide slope phase is proposed. This approach is aimed at reducing the horizontal distance required to land fixed-wing UAVs. A 6-DOF simulation was carried out using this technology to investigate its validity. It was confirmed that the horizontal landing distance could be reduced by up to 64% compared to the conventional short-distance landing technology, which uses a high glide slope angle.

Flight verification experiments were also conducted as a first step to evaluate the highly accurate turn path tracking technology. Results of the flight verification experiment showed that even with a minimum turning radius of 55 m, the target UAV was capable of continuous turning, with the target performance metrics satisfied. Our future goal is to establish this technology through actual flight verification in which the UAV performs both highly accurate continuous turning, deceleration, and descent simultaneously.

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飛行中ワイヤレス電力伝送に向けたドローン飛行制御システムの開発

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本研究では，飛行中ドローンへのワイヤレス電力伝送の実現を目的として，充電時を想定した高精度なドローン飛行制御システムを開発した。具体的には，カメラによるARマーカー位置推定システムとマイクロ波電力伝送を模擬した光源位置推定システムを開発し，それぞれの位置推定システムを用いてドローン制御実験を実施した。ARマーカー位置推定システムは遅延が大きくドローンの傾き補正によって精度が低下するのに対し，光源位置推定システムは高精度かつ低遅延で位置が推定可能である。一方で，ARマーカーを用いる場合はカメラの画角に応じて比較的広い範囲で制御可能であるのに対し，光源位置推定システムは制御可能範囲がビームの照射範囲に限定されることが明らかとなった。

Keywords: 光源位置推定，信号強度，ARマーカー，リアルタイム制御，ドローン制御，ワイヤレス電力伝送

Development of Drone Flight Control System for In-flight Wireless Power Transmission

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In this study, we developed a high-precision drone flight control system to enable wireless power transmission to drones in-flight, particularly during charging operations. Specifically, an AR marker-based position estimation system using a camera and a light source position estimation system simulating microwave power transmission were developed. We conducted drone control experiments with both systems to evaluate their accuracy, latency and operation range. The findings demonstrated significant differences between the two systems. The light source position estimation system achieved high accuracy and low latency, making it suitable for applications requiring high-prediction position estimation. However, its controllable range was limited to the beam's illumination area. In contrast, the AR marker-based system allowed for control over a comparatively broader range based on the camera's field of view, despite experiencing high latency and reduced accuracy caused by drone tilt corrections.

Keywords: Light source position estimation, Signal strength, AR Marker, Real-time control, Drone control, Wireless power transmission

1. はじめに

近年，ドローンは物流，監視，災害救助など多様な分野で活用されている。しかし，電動式ドローンにおけるバッテリー持続時間の制約は，依然として大きな課題である。この問題を解決する手段として，ワ

イヤレス電力伝送技術の研究が進められている [1, 2]。特に，飛行中のドローンに向けてマイクロ波ビームの指向性を制御するための機構（電子的または機械的）を必要とする場合，非常に高コストとなる。そのため，直上に放射したマイクロ波ビームに対してドローン自身を移動・制御することを想定した研究も進められている [3, 4]。このシステムにおいては，ドローンが給電スポットの上空で高精度にホバリングするためのリアルタイム制御が不可欠である。

給電スポットの上空にドローンをホバリング制御する方法として3つ（GPS，カメラ，電磁波）が考えられる。まず，RTK-GPS（Real-Time Kinematic GPS）はGNSS値を利用することでセンチメートル単位の位置情報を提供可能にする [5]。しかし，この方法は安定したネットワーク接続を必要とし，特に複雑で高度なシステムにより冗長性を確保しなければ，不安定なネットワークにより，予期せぬ遅延が発生し，正確なホバリングが不可能となる。そのため，任意の場所から給電スポット付近に近づく際に有効と考えられるが，ホバリングの安定性には課題が残る。次に，送電アンテナにARマーカーを装荷し，ドローンに搭載したカメラを用いて上空から撮影し，画像処理によって相対位置を検出する方法が考えられる [6, 7]。この手法はGPSと比較してさらに高い精度が期待される一方，ドローンに搭載可能な性能のマイクロコンピュータを使用した画像処理は計算リソースの制約により，遅延時間が比較的大きいことが予想される。最後に，ワイヤレス電力伝送に用いるマイクロ波ビームを検知し，その位置を推定する方法が考えられる [8]。この手法は，あらかじめビームの放射特性を知っておく必要があるものの，計算リソースが小さく，信号対雑音比が高いため，高精度かつリアルタイムな制御が可能である。ビームが照射される狭い範囲においては特に有効な方法であると言える。

本研究では，GPSに依存しない制御方法に焦点を当て，ARマーカーを利用した制御方法とマイクロ波ビームを模擬した光を利用した制御方法 [9-12] による制御精度を比較するホバリング制御実験を実施した。本実験では，両者ともドローンに搭載したRaspberry Pi 5を用いて位置推定および制御を行うことで，地上の無線通信による制御遅延を排除した。

2. ドローン飛行制御に向けた位置推定システム

本研究では，ARマーカーを利用した制御方法（以下「ARマーカー位置推定システム」）と光を利用した制御方法（以下「光源位置推定システム」）を比較し，ドローン飛行制御精度を評価する。

2-1　ARマーカー位置推定システム

2-1-1　マーカーの選定

カメラ認識により情報を取得可能なマーカーには様々な種類が存在し，用途に応じて適切な選択が必要である。本研究では，カメラ画角内における単一マーカーの位置を高精度かつ低遅延で特定することを目的としている。そのため，低解像度にして計算リソースの負担を抑えたとしても，高い検出性能を実現可能なマーカーとして，6×6ビットのバイナリパターンを持つARマーカーを採用した。このARマーカーは，白と黒の正方形で構成されるグリッド構造を持ち，低解像度の画像においてもコントラストのある領域として認識されやすい特徴を有する。また，6×6ビットのパターンは，誤認識を防ぐために十分な情報量を持ちつつ，低解像度での認識を可能にする適切なセルサイズを確保できる。これにより，計算負荷を抑えながらも，安定したマーカー検出を実現できる [6, 7]。

検出および位置推定には，**図1**に示すArUcoライブラリのARマーカー（ID＝1）を利用した。このライブラリは，マーカーのリアルタイム認識において高い信頼性を誇るオープンソースソフトウェアである。特に，カメラ校正パラメータ（内部パラメータおよび歪み係数）とマーカーサイズを事前に設定することで，カメラ画像上のピクセル座標から実空間の三次元座標への変換を高精度に行うことができる。なお，パターンの違いによる性能差はないため，異なるIDのマーカーを用いることもできる。

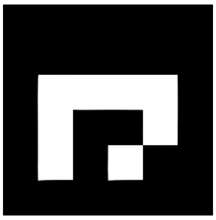


図１　6×6 ビット AR マーカー（ID＝1）

2-1-2　カメラの選定

本研究では，Raspberry Pi Camera Module 3 を採用した。選定理由は，軽量かつコンパクトな設計でドローン搭載に適していること，必要以上の高解像度は計算リソースを大きくするため不要であること，さらに Raspberry Pi 5 との高い互換性によりシステム連携が容易であることである。ドローンとカメラおよび AR マーカーの位置関係を**図２**に示す。ドローンを原点とし，AR マーカー (x, y, z) を z 軸負の方向に向けて設置する。また，カメラはドローン下部に z 軸正の方向に取り付けることで，AR マーカーを視認できるようにしている。

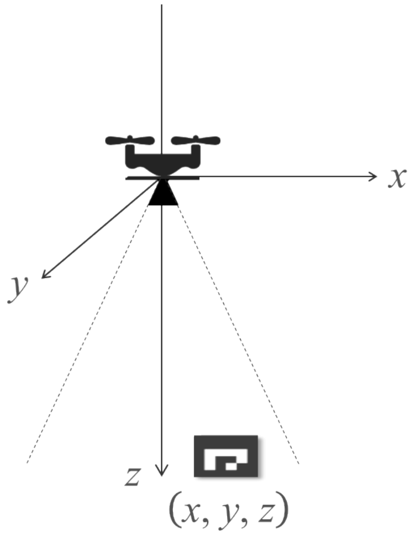


図２　AR マーカーとドローンの位置関係

2-1-3　カメラの傾きによる推定位置の補正

ドローンがロール（横方向の傾き）およびピッチ（前後方向の傾き）を持つ場合，その機体に固定されたカメラも同様に傾く。この結果，AR マーカーの位置がカメラ座標系において傾きを反映した形で計測されるため，**図２**の座標系において正確な位置推定ができない。そこで本研究では，カメラの傾きを補正し，ドローンおよびカメラが鉛直状態であったと仮定した場合の AR マーカー位置を推定する手法を採用した。この手法では，ドローンの姿勢角（ロール角およびピッチ角）をリアルタイムで取得し，その情報を基に回転行列を構築して位置補正を行う。具体的には，カメラの傾きを示す回転行列 $\boldsymbol{R}$ を構築し，カメラ座標系で計測された AR マーカーの位置ベクトル $\boldsymbol{P}_{\mathrm{observed}}$，ドローンおよびカメラが傾いていなかった場合に対応する補正後の位置ベクトル $\boldsymbol{P}_{\mathrm{corrected}}$ を用いて補正を行った。回転行列 $\boldsymbol{R}$ は以下のように計算される。

$$\boldsymbol{R} = \boldsymbol{R}_{\mathrm{roll}} \cdot \boldsymbol{R}_{\mathrm{pitch}} . \tag{1}$$

ロール角 φ に基づく回転行列 $\boldsymbol{R}_{\mathrm{roll}}$ およびピッチ角 θ に基づく回転行列 $\boldsymbol{R}_{\mathrm{pitch}}$ は以下のように表される。

$$\boldsymbol{R}_{\mathrm{roll}} = \begin{bmatrix} \cos\varphi & 0 & \sin\varphi \\ 0 & 1 & 0 \\ -\sin\varphi & 0 & \cos\varphi \end{bmatrix}, \qquad \boldsymbol{R}_{\mathrm{pitch}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix}. \tag{2}$$

以下の変換式によって補正を行った。

$$\boldsymbol{P}_{\mathrm{corrected}} = \boldsymbol{R}^{-1} \cdot \boldsymbol{P}_{\mathrm{observed}}\,. \tag{3}$$

2-2　光源位置推定システム

2-2-1　光源の設定

本研究では飛行中ドローンに対する高精度な制御を目的としているため，光強度に大きな差が生じる指向半値角2.5° という狭い放射角の光源（スタンレー株式会社 LLM0854A/LIGHTING EQU50:5000K）を使用した。ドローンと光源の位置関係を**図3**に示す。ドローンを原点とし，光源位置 (x, y, z)，受信点位置 (x_i, y_i, z_i)，光源の照射方向 $\boldsymbol{L} = (0, 0, -1)$ とする。また，光源からある受信点に向かう光の伝播ベクトルを $\boldsymbol{D}$ とする。

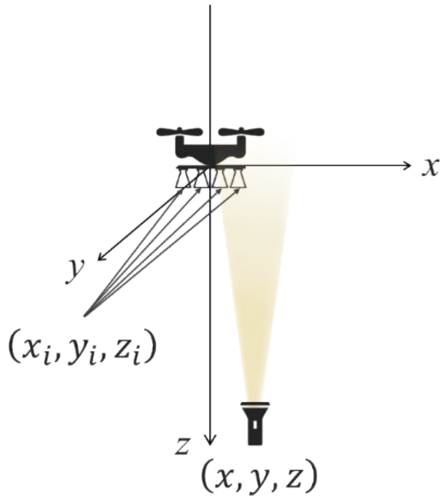


図3　光源とドローンの位置関係

2-2-2　光強度分布のモデル化

受信点を用いて環境光が計測上無視できる空間で光強度を計測し，関数フィッティングを用いて光の強度分布 $\hat{I}$ [mA] を数学的なモデルとして表現する。指向性 G_r はフィッティング係数 σ を持つ角度 θ のガウス関数を用いて**図4**に示すようにフィッティングを行った。その結果，$\sigma = 0.0156$ となった。距離減衰 I_d [mA] はフィッティング係数 a, b を持つ距離 d[m] の逆二乗の関数を用いて**図5**に示すようにフィッティングを行った。その結果，$a = 3.484, b = 0$ となった。b は環境光の影響を受ける定数項である。

$$\hat{I} = G_r \cdot I_d = \left(\frac{a}{d^2} + b\right) \cdot \exp\left(-\frac{\theta^2}{2\sigma^2}\right). \tag{4}$$

d, θ は以下のように表される。

$$d = \sqrt{(x_n - x)^2 + (y_n - y)^2 + (z_n - z)^2}\,. \tag{5}$$

$$\cos\theta = \frac{\boldsymbol{D} \cdot \boldsymbol{L}}{|\boldsymbol{D}||\boldsymbol{L}|}. \tag{6}$$

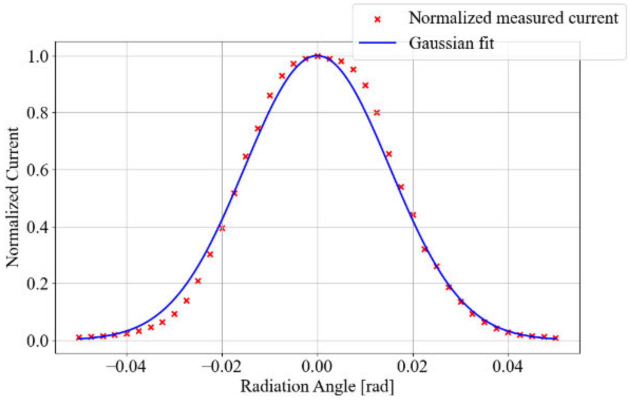


図 4　光強度測定とフィッティング（指向性）

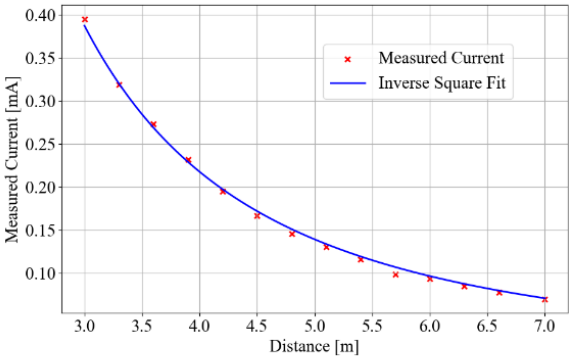


図 5　光強度測定とフィッティング（距離減衰）

2-2-3　誤差関数の構築

受信された光強度 I_i [mA] と理論上の光強度 $\hat{I}\,(x, y, z)$ の誤差を考慮した誤差関数 $f\,(x, y, z)$ を式 (7) のように定義する。この式は，各受信点 i から得られた I_i と $\hat{I}$ の差の二乗和を表している。誤差関数が最小となる位置が，最も適切な光源位置であると推定される。

$$f(x, y, z) = \sum_{i=1}^{N} \left(I_i - \hat{I}\right)^2 . \tag{7}$$

2-2-4　誤差関数の最適化

最急降下法を用いて，誤差関数を最小化するパラメータ（光源位置）を反復的に調整し，最適解を見つける。具体的には，現在の位置から誤差関数 $\nabla f\,(x_k, y_k, z_k)$ の勾配ベクトル $\nabla f\,(x_k, y_k, z_k)$ に従ってステップサイズ $\alpha_x, \alpha_y, \alpha_z$ を移動させることで誤差関数の値を減少させる。この式を (8) に示す。

$$\begin{bmatrix} x_{k+1} \\ y_{k+1} \\ z_{k+1} \end{bmatrix} = \begin{bmatrix} x_k \\ y_k \\ z_k \end{bmatrix} - \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix} \nabla f(x_k, y_k, z_k) . \tag{8}$$

2-2-5　受光基板

今回開発する受光基板は**図 6** に示すように，受信点は格子状に 9 個配置し，各受信点の間隔は 7 cm とした。これは，モーター間距離が 50 cm のドローンに搭載可能なサイズであり，推定精度，推定速度が高くなることを考慮したものである。光強度検出素子としてはフォトダイオードおよびフォトトランジスタが代表的であるが，本研究では応答速度の観点からフォトダイオード（Hamamatsu Photonics K.K.:S6775）を選択した。一般に，2–2–3 の誤差関数では，受信側の指向性を考慮する必要がある。しかし，本研究では，光がフォトダイオードに対して傾斜する場合であっても，その指向性の影響が実験条件下で無視できる範囲に留まることを確認した。そのため，本実験では受信側の指向性を考慮しないものとする。各フォトダイオードの回路図を**図 7**，開発した受光基板を**図 8** に示す。5 V の逆バイアス電圧を印加し，フォトダイオードが生成する光電流を電圧 V_{out} に変換するために最大抵抗値 20 kΩ の可変抵抗を用いて 10 kΩ 程度で使用する。これにより，キャリブレーションが可能となる。変換された電圧信号は，アナログ-ディジタル（AD）コンバータを経由して Raspberry Pi 5 に入力される。Raspberry Pi 5 上で実行されるアルゴリズムにより，光源位置の推定を行うことでドローンのスタンドアロン，低遅延制御が可能となる。

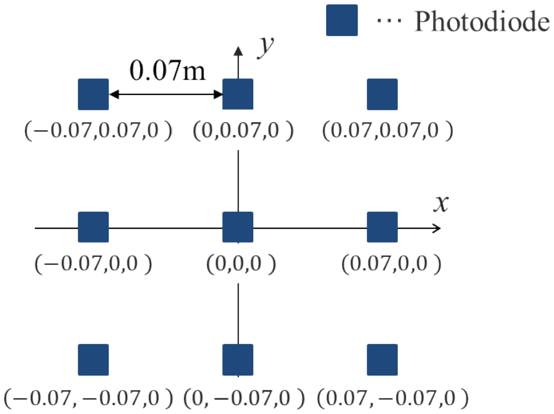
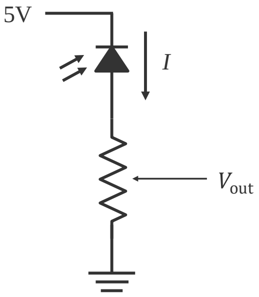


図 6　受光点配置



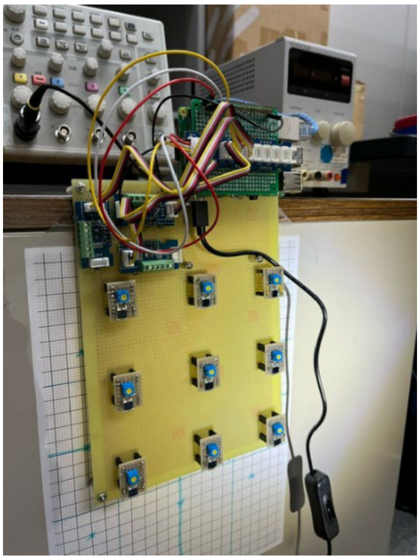


図 7　フォトダイオード回路

図 8　フォトダイオードアレイ基板

3. 飛行制御実験

今回の飛行制御実験には，**図 9** に示す Holybro PX4 Development Kit-X500 v2 を使用した。このドローンにはフライトコントローラーとして Pixhawk 6X，制御ソフトウェアとして ArduPilot を採用している。制御信号は Raspberry Pi 5 から Pixhawk 6X に対して UART を使用して送信する構成とした。本研究では，それぞれの制御方法の性能を評価するため，GPS を用いた位置制御を行わず，高度維持モードを使用した。このモードはドローンの高度を一定に維持する一方で，ホバリングモードとは異なり，ドリフト（水平移動）を補正しない。そのため，制御を行わない場合このドローンはモーター等のばらつきにより任意の方向に約 1.5 m/s の速度でドリフトする。実験の課題は，このドリフトに対して，各制御アルゴリズムがどの程度有効に機能するかを評価することである。

3-1　制御遅延時間の比較

制御遅延は，制御に用いるデータの処理時間による「情報遅延」と，制御の実行間隔による「制御周期遅延」の 2 種類に分類できる。本研究では，AR マーカー位置推定システムと光源位置推定システムのそれぞれにおける制御遅延時間を Raspberry Pi 5 を使用して測定した。その結果を**図 10，11** に示す。測定では，位置推定に必要な電圧値および画像データの取得をノイズ軽減と遅延削減のバランスを考慮して 3 回行い，その平均値を用いた。また，AR マーカー位置推定システムでは，計算リソースとマーカー認識

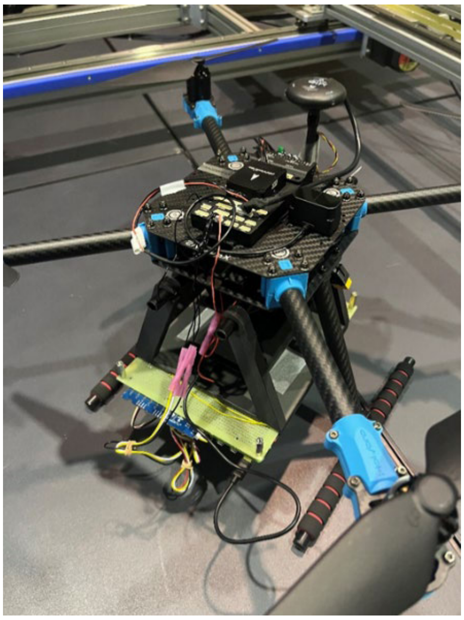


図 9　Holybro：PX4 Development Kit - X500 v2

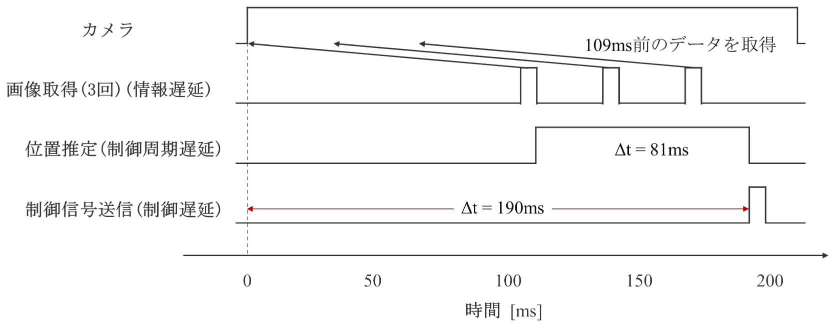


図 10　AR マーカー位置推定システムのタイムチャート

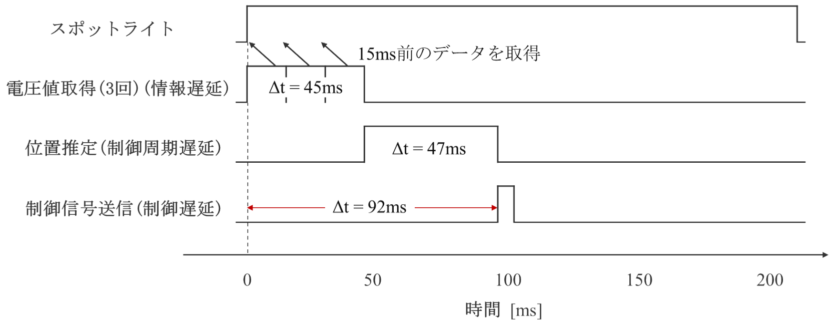


図 11　光源位置推定システムのタイムチャート

率のバランスを考慮し，画像の解像度を 640×480 px に設定した。一方，光源位置推定システムでは，光を検知可能範囲内で十分な精度が得られるよう，最急降下法の試行回数を 10 回に設定した。測定結果から，AR マーカー位置推定システムと光源位置推定システムの制御遅延時間を比較した結果，光源位置推定システムは情報遅延および制御周期遅延の両面で AR マーカー位置推定システムよりも小さい値を示した。

情報遅延は，AR マーカー位置推定システムは 109 ms，光源位置推定システムは 15 ms という結果になった。AR マーカー位置推定システムではカメラからの画像取得，光源位置推定システムでは光センサーか

らの電圧値取得が情報遅延の主な要因である。電圧値のデータは画像と比較してデータ量が小さいため，短時間で処理が可能であり，情報遅延が小さくなったと考えられる。

制御周期遅延について，AR マーカー位置推定システムは 81 ms であり，光源位置推定システムは 47 ms という結果になった。AR マーカー位置推定システムでは認識アルゴリズムによる画像処理，光源位置推定システムでは最急降下法による最適化が制御周期遅延の主な要因である。AR マーカー位置推定システムでは画像取得後，認識アルゴリズムを用いて位置推定を行い，これを 3 回繰り返して平均化する。一方，光源位置推定システムでは 3 回のデータ取得および平均化後，最急降下法を用いて位置推定を行う。そのため，光源位置推定システムの方が位置推定のプロセス回数が少なく，制御周期遅延が小さくなったと考えられる。

3-2　飛行制御実験結果

AR マーカー位置推定システムと光源位置推定システムについて，高度 4 m において AR マーカーおよび光源上空にホバリングさせる飛行制御実験を行った。まず，AR マーカー位置推定システムにおいて最適化した PID ゲインを光源位置推定システムに適用した場合，光の検知範囲がカメラの視野角と比較して小さいため，ドリフトに対して制御量が不足し光の検知範囲を外れる結果となった。一方で，光源位置推定システムにおいて最適化した PID ゲインを AR マーカー位置推定システムに適用した場合，カメラの視野角が光の検知範囲と比較して大きいため，速度が過大になり AR マーカーが検知できなくなる結果となった。以上から，それぞれ最適な PID ゲインを設定した。

ドローンが高速で動く場合，カメラで取得する映像にブレが発生し，AR マーカーの認識が困難となる。この問題に対し，シャッタースピードを高速化することで映像のブレを抑制可能だが，光の取り込み量が減少し画面が暗くなる。画面が暗くなりすぎると，AR マーカーを取得できなくなるため，今回はブレ抑制と光量のバランスを考慮してシャッタースピードを 1 μs に設定した。また，AR マーカーの一辺のサイズは安定した認識が可能な 30 cm とした。

各システムで推定された位置情報を基にドローンの軌跡を**図 12**，**13** にプロットした。その結果，光源位置推定システムはより高精度に光源上空付近をホバリング可能であることが確認された。この結果は，情報遅延および制御周期遅延がより小さいことで応答性が優れていることが要因と考えられる。一方，AR

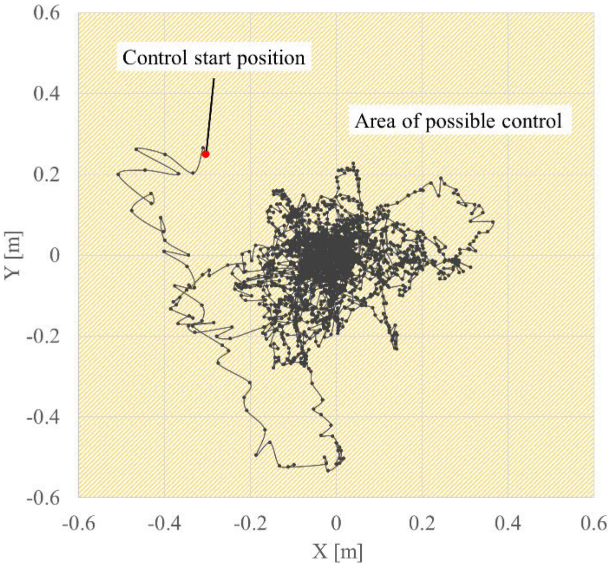


図 12　AR マーカー位置推定システム制御によるドローンの軌跡

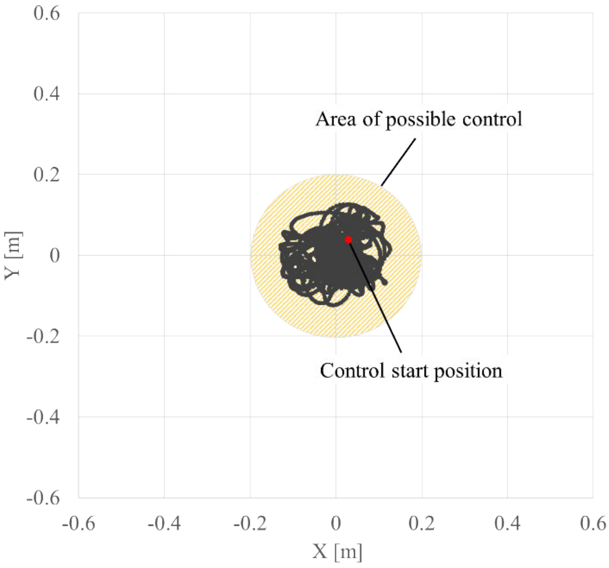


図 13　光源位置推定システム制御によるドローンの軌跡

マーカー位置推定システムの軌跡は滑らかではない。これは，カメラの傾き補正に使用したフライトコントローラーのセンサーが実際の傾きとわずかに誤差があるデータを取得した場合に，4 m先のARマーカーの位置推定結果には大きな誤差として現れるためである。この誤差はPID制御のD成分に大きく現れるため，今回設定したDゲインより大きくすると，傾き補正による誤差に敏感に反応し，ドローンが急激に傾くため，安定した飛行が困難になることが確認された。

また，ARマーカー位置推定システムはより広い範囲で位置推定および制御が可能であることが確認された。ARマーカー位置推定システムによる制御可能範囲は，カメラの画角に依存し，本実験では短辺が2.8 mの長方形領域となった。光源位置推定システムによる制御可能範囲は，各受光点で位置推定可能な十分な受光強度の差が得られることによって決定される。本実験では半径0.2 mの円形領域となった。この結果によって，ARマーカー位置推定システムが広範囲な制御に適している一方で，光源位置推定システムは限定された領域内での高精度制御に適していることが示された。

4. まとめ

本研究では，ARマーカー位置推定システムと光源位置推定システムを用いてそれぞれのドローン飛行制御性能を評価した。その結果，ARマーカー位置推定システムは遅延が大きくドローンの傾き補正によって精度が低下するが，カメラの画角に応じて比較的広い範囲で制御可能であるのに対し，光源位置推定システムは高精度かつ低遅延で位置が推定可能であるが，制御可能範囲がビームの照射範囲に限定されることが明らかとなった。この特性から，ワイヤレス電力伝送を行う際には給電スポットからの距離に応じて制御方法を切り替えるアプローチが有効であると考えられる。具体的には，給電スポットから最も遠い領域ではRTK-GPSを使用し，給電スポット付近ではARマーカー位置推定システムを使用，給電スポット直上ではマイクロ波ビームを検知し，その位置を推定するシステムを使用することで，ワイヤレス電力伝送における高精度かつ効率的なホバリング制御が実現可能である。本研究の成果は，バッテリー持続時間というドローンの課題を解決するための実用的な基盤技術として貢献が期待される。また，今後は情報遅延および制御周期遅延の改善により，さらに位置制御精度の高いドローンの開発が求められる。

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2025年はJUIDA未来創生元年

一般社団法人日本UAS産業振興協議会
理事長　鈴木　真二

Technical Journal of Advanced Mobility（次世代移動体技術誌）は2020年に創刊され，今年で6年目を迎えました。技術だけでなく，制度や，教育活動の分析など次世代移動体に関する論文や報告の発表の場として，国内外から多くの関心を集め，アクセス数も月1,100件を超えるまでに成長しました。引き続き，アカデミアのみならず，産業界，研究機関，行政機関など，あらゆる分野からの先進的な取り組みや知見の発表をお待ちしております。

一般社団法人日本UAS産業振興協議会（JUIDA）は，2025年に設立11年目を迎えました。この節目にあたり，私たちはこれまでの活動を振り返るとともに，新たなドローンおよび空飛ぶクルマ産業の振興に一層取り組む決意を新たにしています。産業の健全な発展を支えるべく，人材育成，安全運航の推進，関連技術の標準化，そして国際的な連携強化に取り組み，次世代モビリティ社会の構築に寄与してまいります。

小型無人航空機「ドローン」に関しては，2023年12月のレベル3.5飛行も新たに制度化され，2024年度には物流や災害対応での本格運用が全国的に展開されました。特に，能登半島地震災害を契機に，ドローンを活用した被災地支援は社会的認知をさらに高め，物資輸送や捜索活動においてもその充実が官民の目標と掲げられています。JUIDAでは引き続き，災害時における迅速な対応体制の強化を進めるべく，自治体，自衛隊との連携を深める取り組みを継続し，また，災害時のドローン活用の知識を体系化した「ドローン防災スペシャリスト教育」プログラムを開始しました。

さらに，2025年は「空飛ぶクルマ（eVTOL）」の実用化に向けた飛躍の年でもあります。2025年大阪・関西万博では，eVTOLの試験飛行が会場周辺で実施され，未来技術のショーケースとしての注目を集めることと思います。今後の，日本国内の都市や観光地でも実証実験の加速が期待されます。ドローン技術の発展は，空飛ぶクルマの様々な技術や安全管理にも応用され，両者の技術的融合が進み，次世代エアモビリティーとして体系化されていきます。JUIDAとしても，関連産業の発展を後押しすべく，産業界や行政との協力体制を強化し，産業振興支援を積極的に進めてまいります。

2025年度は，これまでの成果を基盤に，次世代エアモビリティーの社会実装を一層推進すべく，「JUIDA未来創生元年」と位置づけます。医療，物流，農業，建設など多様な分野での実用化を進め，安全性と利便性の両立を追求し，持続可能な未来社会の実現を目指して取り組んでまいります。Technical Journal of Advanced Mobilityも，その一翼を担い，技術と社会をつなぐ架け橋であり続けることをお約束いたします。

2025年3月吉日

理事長
鈴木　真二/Shinji Suzuki
東京大学 名誉教授。東京大学 未来ビジョン研究センター 特任教授。1953年岐阜県生まれ。79年東京大学大学院工学系研究科修士課程修了。（株）豊田中央研究所を経て，東京大学大学院工学系研究科航空宇宙工学専攻教授を2019年に定年退職後，現職。工学博士，専門は航空工学。日本航空宇宙学会会長（第43期），国際航空科学連盟（ICAS）会長（2019-2020），福島ロボットテストフィールド所長など。著書に，『飛行機物語』（筑摩書房），『現代航空論』（編著，東京大学出版会），『落ちない飛行機への挑戦』（化学同人社），『ドローン活用入門：レベル4時代の社会実装ハンドブック』（編著，東京大学出版）などがある。

編隊飛行ドローンの飛行安定性解析と網掛け作業への応用

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近年，活躍の場を広げているドローンは，複数台を編隊飛行させることで作業効率が上昇し，使用用途がさらに拡大することが期待できる。しかしながら，複数台の飛行によって発生する気流の影響により，衝突する危険性が増してくる。そこで本研究では，編隊飛行しているドローン同士が互いに衝突することなく，安定に飛行する条件を明らかにするため，2台のドローンまわりの流体シミュレーションを実施した。その結果，2台のドローンの設置間隔とプロペラから発生する流速から算出されるレイノルズ数 Re が 2.0×10^5 以上の時に，ドローン間の差圧がほぼ無くなり，引き合うことなく安定に飛行できることを確認した。また，上記のシミュレーション結果を確認する実験を，機体幅0.1 mのドローンで行い，2台のドローンの設置間隔0.4 m（$Re = 2.0 \times 10^5$）の時は安定に飛行することを確認した。さらに，設置間隔0.6 mのドローンを4台編隊飛行させて，室内での網掛け作業への応用を行った。その結果，ドローンの移動と旋回制御を組み合わせることで，高さ0.9 mの木の模型の上に，網をリリースする作業ができることを確認した。

Keywords: ドローン，編隊飛行，流体シミュレーション，網掛け作業

Flight Stability Analysis of Formation Drones and Application to Netting Operation

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In recent years, drones have been expanding their field of application, and their use can be expected to further expand as their work efficiently using the flight in formation. However, flying with multiple drones entails the risk of collision. Therefore, in this research, flow simulations of two drones were conducted to confirm the conditions of flight stability in formation without collision each other. As a result, it was confirmed that when the Reynolds number calculated from the distance between two drones and the flow velocity induced from the propeller is 2.0×10^5 or more, the differential pressure becomes decrease without collision each other. Two drones flight in formation experiments were conducted to confirm the above simulation results. It was confirmed that the drones crashed and collided with the distance of 0.1 m, but the drones stably stayed with the distance of 0.4 m ($Re = 2.0 \times 10^5$). Moreover, four drones with the distance of 0.6 m were flown in formation for the application to netting operation indoor. As a result, it was confirmed that the four drones could release nets on the cardboard tree model with the height of 0.9 m by the combination of movement and rotation control.

Keywords: Drone, Formation flight, Fluid simulation, Netting operation

1. はじめに

無人航空機（以下，「ドローン」という）は，その開発の歴史は古いが，2010年代になってから，各種産業分野への普及が飛躍的に進んだ［1］。例えば農業分野では，農作物への農薬散布［2］，害虫，害獣駆除［3］，および空撮画像を撮影することによる生育状況の管理［4］が行われている。また，その他の産業分野では，その使用範囲が拡大し，市街地や山奥の集落，離島などへの輸送物の運搬［5］や，高速道路橋や建設現場［6］などの高所や危険な場所での設備点検作業に，主に用いられ始めている。これらの作業は，観測エリア，ペイロード，および時間短縮の点で，複数台の編隊飛行で，さらに効率が上昇することが期待できる。

このような状況の中で，編隊飛行するドローンを利用した先行研究として，編隊飛行時の制御方法の研究が行われている。具体的には，ドローンに自律性を持たせ，ランダムな障害物がある環境下でも編隊飛行中に周囲情報を共有する飛行制御方法［7-9］，GPS（Global Positioning System）に依存しないで前方ドローンを追随する飛行方法［10］，マルチロータヘリコプタを用いた衝突回避を考慮した誘導制御法［11］，およびモーションキャプチャーを利用した3次元空間で機体間隔を一定に保つ制御法［12］などが行われている。また，ドローンではないが，固定翼型飛行機の編隊飛行では，NASA（National Aeronautics and Space Administration）が，後方に発生する渦を揚力に活用して燃費を向上させる研究を，流体シミュレーションを活用して実施している［13-16］。このような状況の中で，編隊飛行ドローンの第1の課題は，汎用的に使用されているドローンが複数台飛行する際の安定条件を，流体シミュレーションなどを活用して明らかにした研究はほとんどないことである。

一方，編隊飛行の利用分野としては，intel® は自社の PREMIUM DRONE［17］を500台以上用いて，2018年の平昌オリンピック［18］での五輪マーク，および2021年の東京オリンピック［19］での地球儀のパフォーマンスに用いられた。このような状況の中で，編隊飛行ドローンの第2の課題は，編隊飛行するドローンを活用して，人の手が届かない高所での作業援助，あるいはビニールハウス内などの屋内においての農作業の援助に応用されている例は，ほとんどないことである。

そこで本研究では，上記の2つの課題を解決することを目的として，流体シミュレーションを用いて，ドローンの編隊飛行の安定飛行条件を明らかにするとともに，その結果を踏まえてビニールハウス内などの室内での網掛け作業を，以下の手順に従って実施した。

まず第2章では，流体シミュレーションを用いて，2台の編隊飛行しているドローン同士が衝突することなく，安全に飛行することができる条件を明らかにした。次の第3章では，本研究に用いるドローンおよび網掛け作業を行う際の網の設計仕様を示した。さらに第4章では，ペイロードと操作性を考慮し，網掛け作業を行うためにドローンに装着するジョイントの設計，試作を行った。そして第5章では，試作を行ったジョイントを装着して，室内にある木の模型への網掛け作業の実験を行った結果を報告する。

2. 流体シミュレーション

2-1　安定飛行条件の解明

離陸させて編隊飛行下にあるドローンの安定飛行条件を明らかにするために，2台のドローンまわりの3次元流体シミュレーションを実施した。使用した流体シミュレーションソフトは，Flowsquare^{+}［20］であり，**図1**に解析領域と境界条件を示す。ここで，図中のLは2台のドローンの設置距離，Hは地面からの高さである。また，lxはx方向，lyはy方向，およびlzはz方向の長さ（紙面垂直方向）である。一方，ドローンのプロペラ部の境界条件は，回転によりプロペラ上部から流入する流速VinG（緑色領域），プロペラ下部から流出する流速VinR（赤色領域）を与える方法を採用した。なお，図の煩雑さを避けるため，VinGとVinRはドローン1のみに記載しているが，ドローン2に関しても同様の境界条件を設定している。

表1は，流体シミュレーションの解析領域の寸法と境界条件で使用した14種類のパラメータの値を示

している。本シミュレーションでは，**表 1** の右欄に示しているように，typeA（ドローン幅 $W=0.20$ m，プロペラ直径 $D=0.08$ m）と typeB（ドローン幅 $W=0.30$ m，プロペラ直径 $D=0.12$ m）の 2 種類の小型ドローンを対象にした。解析領域の x，y，z 方向の長さである lx，ly，lz，各方向の格子分割数である nx，ny，nz は**表 1** に示す値をそれぞれ採用し，typeA と typeB では，幾何形状が相似形になるようにした。なお，本シミュレーションでは，**図 1** の紙面垂直方向である Z 方向を薄くした疑似 2 次元的な解析領域を設定した。また，ドローン 1 および 2 のプロペラ上部から流入する流速 VinG（緑色領域），プロペラ下部から流出する流速 VinR（赤色領域）は，ピトー管による 5 回の実測の平均値として，下向きにそれぞれ−8.0 m/s と−12.0 m/s として与えた。なお，空気の粘性係数 mu（293 K）は，1.8×10^{-5} Pa・s とした。さらに，ドローン 1 および 2 の地面からの高さ H は，ホバリング状態を想定として 0.50 m および 0.75 m とした。また，流体シミュレーションを安定に進めるため，陽解法のクーラン数 cfl は小さめの 0.01 とし，2 台のドローン間の距離 L を 0.10～0.40 m および 0.15～0.60 m まで変化させた。

図 2 は，**図 1** に示すモニタリング点（ドローン 1 から距離 $1.5W$，地面からの高さ $0.25H$）での流速収束状況のグラフである。ドローン typeA の場合，モニタリング点における流速は，100,000 step までのシミュレーションで約 3.0 m/s で収束していることを確認した。なお，ドローン typeB の場合も，100,000 step でシミュレーションが収束していることを確認した。

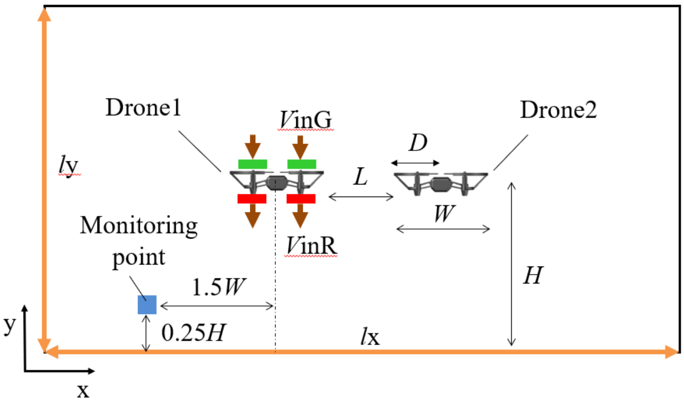


図 1　流体シミュレーションの解析領域と境界条件

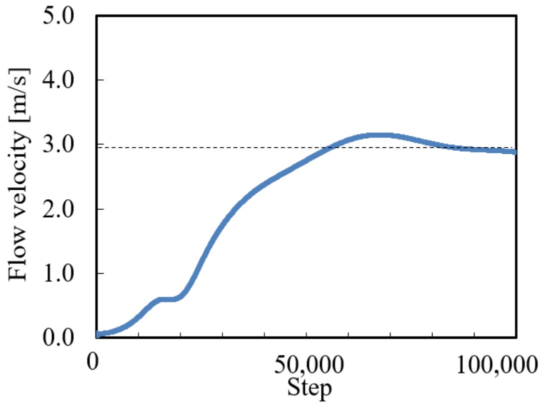
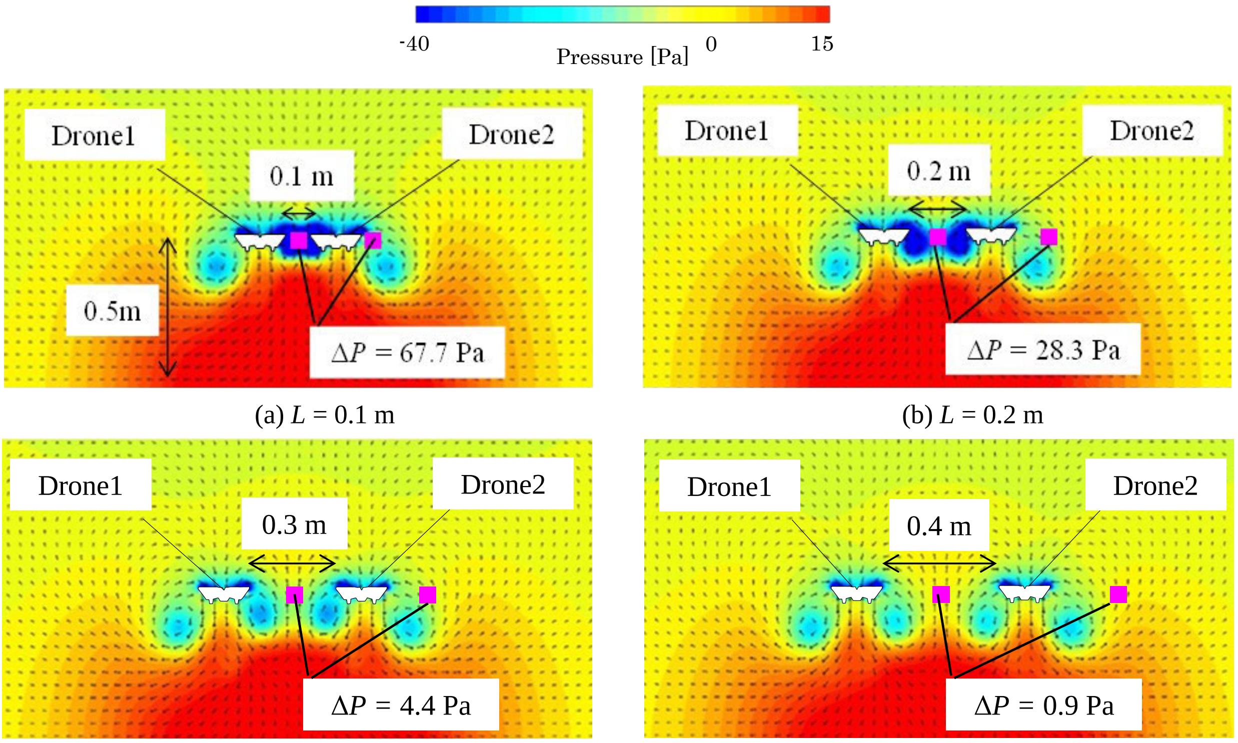


図 2　モニタリング点での流速収束状況（typeA）

表 1　流体シミュレーションの解析領域の寸法と境界条件で使用した 14 種類のパラメータの値

No.	Parameters	Explanation of parameters	Input data	
			Drone-typeA	Drone-typeB
1	W	Width of drone（m）	0.20	0.30
2	D	Diameter of drone propeller（m）	0.08	0.12
3	H	Hovering height（m）	0.50	0.75
4	L	Distance between drones（m）	0.10～0.40	0.15～0.60
5	lx	Length in x direction（m）	2.0	3.0
6	ly	Length in y direction（m）	1.0	1.5
7	lz	Length in z direction（m）	0.05	0.75
8	nx	Number of grids in x direction	500	750
9	ny	Number of grids in y direction	250	375
10	nz	Number of grids in z direction	5	8
11	VinG	Inflow velocity at the top of drone propeller（Boundary color : Green）	−8.0	−12.0
12	VinR	Outflow velocity at the bottom of drone propeller（Boundary color : Red）	−8.0	−12.0
13	mu	Viscosity coefficient（Pa・s）	1.8×10^{-5}	1.8×10^{-5}
14	cfl	Courant-Friedrichs-Lewy number	0.01	0.01

図 3 は，地面からの高さ $H = 0.50$ m でホバリング状態にある 2 台のドローン typeA まわりの xy 平面における圧力分布であり，z 方向の奥行き中央値である 0.025 m での断面を示している。**図 3（a）～（d）** は，2 台のドローンの設置間隔 L が 0.1 m～0.4 m のものであり，カラーバーは圧力の表示範囲で最小値を−40 Pa，最大値を 15 Pa とした。なお，2 台のドローン間の圧力差 ΔP は，図中のピンク色のモニタリング点での 2 点間で圧力差より算出した。すなわち，1 点は 2 台のドローン 1 と 2 の中心で右ドローンの「左端点から $L/2$」の位置，もう 1 点はドローン 2 の「右端点から $L/2$」の位置であり，この 2 点間で圧力差 ΔP を算出した。**図 3（a）～（d）** を見ると，設置間隔 L が広がるにつれて，圧力差 ΔP が減少していき，0.4 m 以上になると圧力差がほとんど無くなっていることがわかる。



(a) $L = 0.1$ m　(b) $L = 0.2$ m

(c) $L = 0.3$ m　(d) $L = 0.4$ m

図 3　2 台のドローン typeA の設置間隔 L を変化させた圧力分布（ホバリング状態 $H = 0.5$ m）

図 4 は，**図 3** で示したシミュレーション結果に基づき，2 台のドローン間のレイノルズ数 Re と圧力係数 C_p の関係をまとめた図である。横軸は，設置間隔 L を式（1）に示すレイノルズ数 Re を用いて無次元化した。ここで，ρ は空気の密度，u はドローンのプロペラ下部から流出する流速，μ は空気の粘性係数である。

$$Re = \frac{\rho u L}{\mu} \tag{1}$$

一方，縦軸は，圧力差 ΔP を式（2）に示す圧力係数 C_p を用いて無次元化した。ここで，ρ は空気の密度，u はドローンのプロペラ下部から流出する流速である。

$$C_p = \frac{\Delta P}{\frac{\rho}{2} u^2} \tag{2}$$

なお，**図 4** には typeA（●印）と typeB（■印）の両方をプロットしている。レイノルズ数 $Re \geqq 2.0 \times 10^5$（typeA の設置間隔 $L \geqq 0.4$ m）の条件，すなわち，2 台のドローン間の距離が大きくなると，圧力係数 C_p が 0 に近

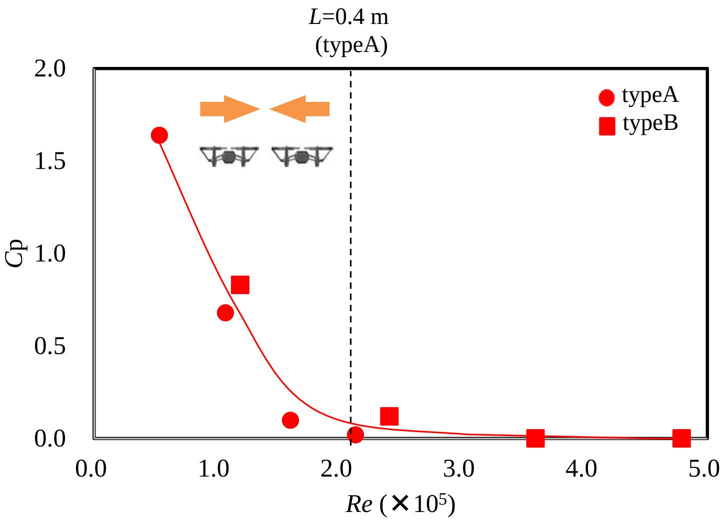


図 4　2 台のドローン間のレイノルズ数 *Re* と圧力係数 C_p の関係

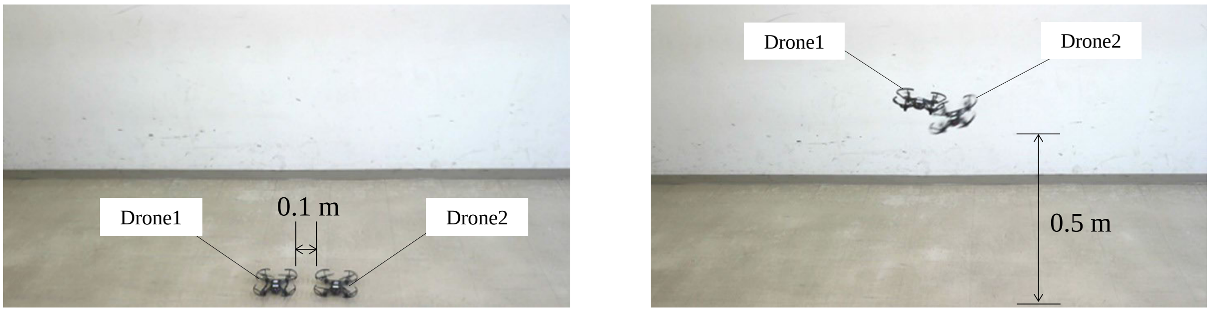
くなり，圧力の影響を受けて引き合うことが無いことを確認できる。

2-2　飛行実験による安定飛行条件の確認

流体シミュレーションから得られた安定飛行条件を確認するために，2 台のドローンによる飛行実験を行った。飛行実験に用いたドローンは，**表 2** に示すスペックを有する Ryze Technology Co. の Tello EDU［21］であり，第 1 章の流体シミュレーションで対象としたドローン typeA である。**図 5** は 2 台のドローンの設置間隔 *L* が 0.1 m（$Re = 0.5 \times 10^5$）の場合，**図 6** は設置間隔 *L* が 0.4 m（$Re = 2.0 \times 10^5$）の場合の飛行実験の写真であり，各図の **(a)** は離陸前，**(b)** は離陸後ホバリング高さ $H = 0.5$ m で 5 秒経過である。2 台のドローンの設置間隔 *L* が 0.1 m である**図 5 (a)** の場合には，離陸後ホバリング高さ $H = 0.5$ m で 5 秒経過した時点

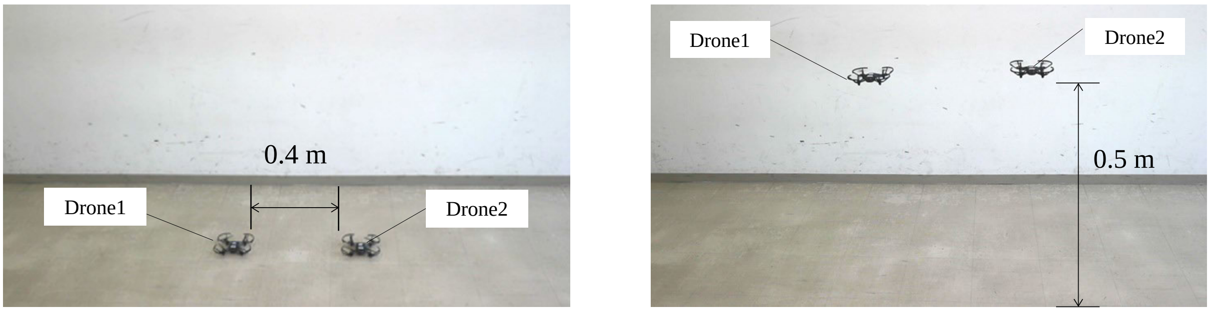
表 2　Tello EDU（typeA）のスペック

Parts	Specification
Body weight［g］	87
Battery［Ah/3.8V］	1.1
Maximum flight length［m］	100
Maximum flight speed［m/s］	8
Maximum flight time［min］	13
Maximum flight attitude［m］	30



(a)　離陸前　　(b)　離陸後ホバリング高さ *H* = 0.5 mで5秒経過

図 5　設置間隔 *L* = 0.1 m の飛行実験（$Re = 0.5 \times 10^5$）



(a)　離陸前　　**(b)　離陸後ホバリング高さ*H*＝0.5 mで5秒経過**

図６　設置間隔 $L = 0.4$ m の飛行実験（$Re = 2.0 \times 10^5$）

で，**図５（b）**に示すようにドローン同士が引き合って衝突していることが確認でき，その後は墜落してしまった。一方，2 台のドローンの設置間隔 L が 0.4 m である**図６（a）**の場合には，離陸後ホバリング高さ H＝0.5 m で 5 秒経過した時点で，ドローンが引き合うことなく，安定に飛行できることが，**図６（b）**に示すように確認できた。

3.　網掛け作業に用いるドローンと網の仕様と制御方法

第 2 章で得られた編隊飛行しているドローンの安定飛行条件をもとに，ビニールハウス内を想定した室内での網掛け作業への応用展開を検討した。作業に用いるベースドローンは，安定飛行条件の確認に使用したのと同様の Tello EDU（typeA）を用いることにした。一方，網掛け作業を行う際に用いる網は，本研究で用いる Tello EDU のペイロードが 30 g であり，網の 4 つの角を 1 台ずつで持つことを想定して 120 g 以内にする必要がある。**図７**は，4 台の Tello EDU が編隊飛行しながら網を保持した状態で移動し，木の模型の上空で網をリリースして網掛けする作業の概要図である。ここで，編隊飛行のドローンは，1 台のパソコンからの wifi 通信で，4 台を同時に制御する方式とした。なお，制御プログラムは，ROBOMASTER TT SDK 3.0 User Guide［22］に記載されている制御コマンドを用いて，Python プログラムによりコーディングした。

4.　網を保持およびリリースするジョイントの設計と試作

次に，**図７**に示した木の模型の上空で網をリリースして網掛けする作業において，必要なパーツである網掛けジョイントの設計と試作について，以下に説明する。**図８**は，網を保持およびリリースするジョイント（緑色）と高さ調節部品（青色）を装着した状態のドローンの 3 次元 CAD（Computer Aided Design）である。ドローンに網掛けジョイント（緑色）を装着させると，機体が地面に対して水平にならないため，プ

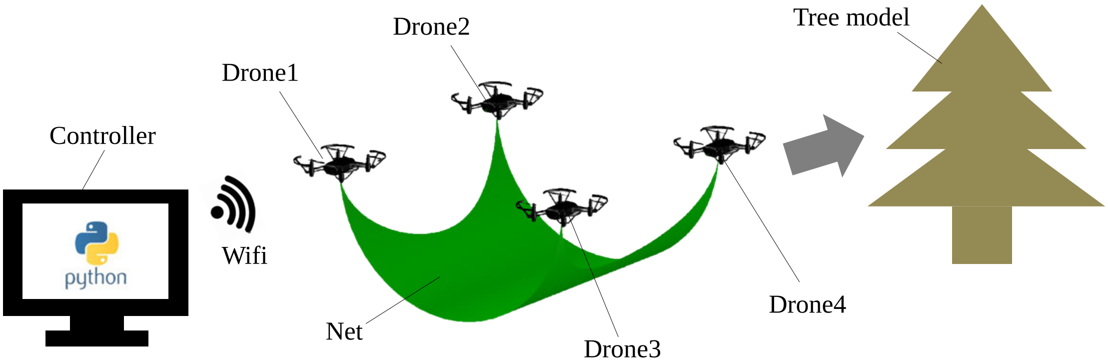
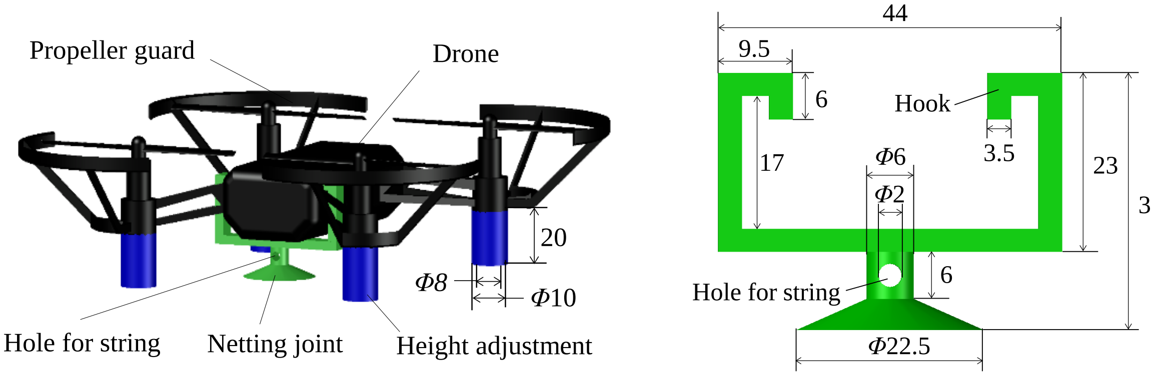


図７　4 台のドローンが編隊飛行しながら網を保持した状態で移動して網掛けする作業の概要

ロペラガード下部に，高さ 20 mm で外径 Φ10 mm および内径 Φ8 mm の中空円筒型の高さ調節部品（青色）を装着している。**図 8（b）**は網掛けジョイントの寸法（mm）であり，積層型の 3D プリンタ da Vinci mini＋[23] で，PLA（Poly-Lactic Acid）樹脂を用いて作成した。なお，ジョイント上方のフック部の厚さは 6 mm，下方の紐巻き付け部は Φ6 mm の円筒に Φ2 mm の孔を設け，その下は底面 Φ22.5 mm の楕円錐台とした。

図 9 は，ジョイントをドローンに装着して，下部の孔に紐を巻き付けた状態の写真である。網から紐にかかる張力を利用して，ドローンが 360° で 4 回転すると，ジョイント下部の孔を通して巻き付いている紐が，ほどけてリリースできる構造になっている。なお，ドローン 1 台に装着する高さ調節部品（青色）×4 とジョイント（緑色）と紐の質量 M は，**表 3** に示すように，2.0＋3.0＝5.0 g となる。



(a) ジョイント装着時のドローン　**(b) ジョイントの詳細形状と寸法 [mm]**

図 8　ドローンに装着する網を保持およびリリースするジョイントの 3DCAD

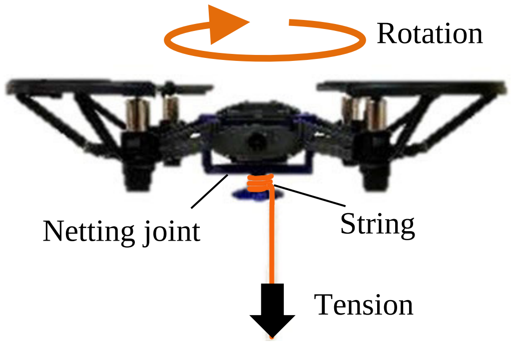


図 9　ジョイントに紐を巻き付けたドローンの写真

表 3　4 台のドローンに掛かる総質量

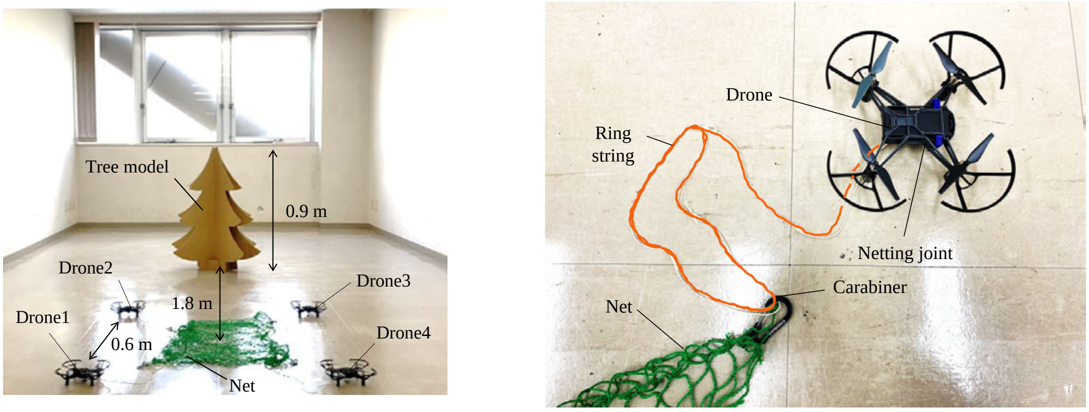
No	Parts	M (g)	N	Subtotal (g)
1	Height adjustment×4	2.0	4	8.0
2	Netting joint with string	3.0	4	12.0
3	Net	59.0	1	59.0
4	Carabiner	5.6	4	22.4
	Total（No.1～4）			101.4

5. 編隊飛行ドローンによる網掛け作業実験

図 10 は，4 台のドローンと木の模型の初期配置である。**図 10（a）**は実験前の写真であり，高さ 0.9 m の段ボール製の木の模型を設置し，そこから 1.8m 離れた位置に網の中心が来るように配置した。4 台のドローンの設置間隔 L は，第 2 章でのシミュレーション結果に基づき，0.4 m 以上である 0.6 m とした。また，**図 10（b）**は，ドローンのジョイントと網（ASTRO CO., LTD 製：サイズ 0.6 m×0.6 m，質量 59 g：**表 3** の No.3）の結合方法を示した写真である。ジョイントに巻きつけている紐の先端に，輪状の糸を介してカラビナ（TITECOUGO 製：質量 5.6 g×4＝22.4 g：**表 3** の No.4）と接続している。ここで，4 台のドローンに掛かる総質量は，**表 3** の No.1～4 に示すパーツの合計で 101.4 g となり，ペイロード 120 g 以内を満たしている。

図 11 は，実験時の詳細な動作の値を示したフローチャートである。Step1 で離陸をさせ，Step2 で 4 台のドローンを同時に 1.5 m 上昇させている。続いて，Step3 で木の模型の位置まで同時に 1.8 m 前進させ，

Step4 で同じく同時に 360° で 4 回転させた。**図 12** は，**図 11** の各フローチャートの写真を示したものである。これらの一連の動作により，室内にある 0.9 m の木の模型に対して，4 台の編隊飛行ドローンを用い て網掛け作業ができることを確認した。



(a) 実験前の写真　　(b) ドローンと網の結合方法の写真

図 10　4 台のドローンと木の模型の初期配置

図 11　飛行制御のフローチャート

(a) Step1 離陸　　(b) Step2 上昇

(c) Step3 前進　　(d) Step4 回転リリース

図 12　4 台の編隊飛行ドローンによる網掛け作業の写真

6. 考　　察

本研究では，流体シミュレーションを用いて編隊飛行しているドローン同士が衝突することなく安全に飛行することができる設置間隔を明らかにしたが，その際に，ドローン typeA の $L = 0.1$ m（**図 3（a）**）に関

しては，シミュレーションの格子分割数の検討も併せて実施した。すなわち，各方向の格子分割数を，$nx=500$ から 1000，$ny=250$ から 500，$nz=5$ から 10 の 2 倍で 3 方向 $=2^3=8$ 倍にしたシミュレーションを実施した。結果として，総分割数を 8 倍にした場合でも，$nx=500$，$ny=250$，$nz=5$ の解析結果はほとんど変わらないことを確認した。そのため，以降のシミュレーションは，総分割数を元に戻して行った。

また，網掛け作業実験においては，4 台のドローンからの網のリリースには成功したが，同時にリリースできないことが残課題となった。今後は，ドローンの状態を常にフィードバックする制御を追加して，網の同時リリースの実現を目指して行く。

さらに，飛行安定性解析はドローン幅 $W=0.2$〜0.3 m の小型ドローンを対象に行い，無次元数のレイノルズ数 Re で整理したが，中型や大型ドローンへの適用を視野に入れた研究を推進して行く予定である。今後，中型や大型ドローンでもレイノルズ数 Re での整理の有効性が確認できれば，安全なドローンの編隊飛行を実現するための指針になり得ると考えている。すなわち，編隊飛行時の接近禁止領域を理論的に設定すること，およびこの内部の圧力の影響を受けて引き合う領域では，これを考慮した飛行制御を行うことなどの指針を示すことができると考えている。

7. おわりに

本研究では，流体シミュレーションを用いて編隊飛行しているドローン同士が衝突することなく安全に飛行することができる設置間隔を明らかにした。さらに，室内にある木の模型に対する網掛け作業実験を行い，以下の結論を得た。

1. 流体シミュレーションを用いて，2 台の編隊飛行しているドローンの安定飛行条件を確認し，レイノルズ数 $Re \geqq 2.0\times10^5$（typeA の設置間隔 $L \geqq 0.4$ m）の条件，すなわち，2 台のドローン間の距離が大きくなると，圧力の影響を受けて引き合うことが無いことを確認した。
2. 上記のシミュレーション結果を確認する実験を行い，2 台のドローンの距離が 0.1 m の時に衝突後に墜落し，0.4 m の時は安定に飛行することを確認した。
3. ドローン自身が回転することで，網をリリースするためのジョイントを設計し，積層型 3D プリンタで作成し，実験で網をリリースできることを確認した。
4. 高さ 0.9 m の段ボール製の木の模型に，設置間隔 0.6 m の 4 台の編隊飛行ドローンで，網掛け作業ができることを確認した。

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2023年3月，国士舘大学機械工学系卒業。2023年4月同大学大学院機械工学専攻に進学。Technical Journal of Advanced Mobility ポスターセッション in Japan Drone 2023で発表。現在，シミュレーションによるドローンまわりの流れの解析，編隊飛行ドローンの制御，および農業分野へのドローンの適用拡大の開発を行っている。

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有線給電給水方式による連続放水ドローンの開発

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本研究では，ドローンの適用範囲拡大の一環として，連続放水の実現を目指した。具体的には，バッテリーの代わりに電源ケーブルによる連続給電，タンクの代わりにホースによる連続給水，および電源ケーブルとホースを束ねてその高さが可変の供給ポートも併用する「有線給電給水」方式の開発を目的とした。本方式では，供給ポートとドローンに荷重を等分に負担することができるため，連続して広範囲に放水を行うことができる。本方式の設計では，ソーラーパネル洗浄を対象として，その洗浄ロボットと同等である 100 m^2 を放水面積の目標とした。その詳細は，高さが 1.2～2.9 m の範囲で可変の供給ポートから，飛行高度 5.0 m，右移動距離 8.8 m となる。次に，上記の放水面積を満たすためのペイロードは，610 g 以上必要であることを算出し，プロペラ直径 10 inch，ピッチ 4.5 inch，回転数 6000 rpm のクアッドドローンを開発した。さらに，開発した連続放水ドローンの飛行検証実験を行い，ペイロードは設計仕様の 610 g 以上の 690 g であること，および放水面積は目標 100 m^2 とほぼ同等の 103 m^2 に連続放水できることを確認した。

Keywords: クアッドドローン，給電ケーブル，ソーラーパネル，供給ポート，連続放水

Development a Continuous Water Discharge Drone with Power Cable and Water Supply Hose

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In this study, we targeted a continuous water discharge drone for extending the applications. The targeted drone was equipped with a power cable and a water supply hose instead of a battery and a tank. In addition, a supply port was set up to tie up the power cable and the water supply hose. By using this supply port, it was possible to support equally the total loads between the supply port and the drone, therefore the water discharge area was wide. The continuous water discharge drone was designed for cleaning solar panels with the target water discharge area of 100 m^2, the same area as the solar panel cleaning robot. The actual developed drone was a quad type with a diameter propeller of 10 inch, propeller pitch of 4.5 inch and propeller rotation speed of 6000 rpm. It was found that the actual payload became 690 g exceeding the designed value of 610 g in the flight experiment using the continuous water discharge drone connected to the power cable and water supply hose. Moreover, it was found that the water discharge area became 103 m^2, nearly equal to the target value of 100 m^2.

Keywords: Quad drone, Power cable, Solar panel, Supply port, Continuous water discharge

1. はじめに

近年，小型無人航空機（以下，「ドローン」という）は，カメラによる監視や情報収集［1-3］などの用途

にとどまらず，放水や噴霧の用途にまで拡大してきている。例えば，インフラ分野では，老朽化した箇所にコンクリート表面含浸材を塗布し，補修を行う研究が行われている [4-6]。農業分野では，農薬噴霧するドローンが開発および使用されている [7-9]。また，消防・防災分野でも消火剤を放水し，消火を行うドローンが開発されている [10-13]。前述のように，様々な分野でドローンから放水や噴霧をさせることで，人の手に代わって作業を行っている。

しかしながら，これらのドローンは，バッテリー交換や水の補充を行う必要がある。そのため，連続作業を行うことができないことが課題となっている。そこで，本研究ではこの課題を解決することを目的として，有線給電給水方式による連続放水ドローンの開発を，以下の手順で行った。

まず，連続放水の分野の中では，活用ニーズが大きいソーラーパネル清掃を対象とした。先行研究では，清掃ロボット [14]，あるいはバッテリー搭載の放水ドローン [15] はあるが，有線給電給水方式による連続放水ドローンはない。そこで，電力と水を，常に連続供給するケーブルとホースを，供給ポートからドローンに接続して飛行させる方式を採用にした。この方式を前提に，ソーラーパネル清掃の目標として，放水面積，移動距離，飛行高度を荷重の観点から設定，CONOPS（Concept of operations）と呼ばれる運用概念を明確にし，第 2 章でまとめた。第 3 章では，第 2 章で設定した目標を満たすドローンの設計仕様を定めた。最後の第 4 章では，上記の目標と設計仕様を満たすドローンを開発し，飛行しながら連続放水する検証実験を行った結果を示す。

なお今回は，目標をソーラーパネル洗浄ロボットの最大洗浄面積に匹敵する 100 m^2 に設定しているが，この面積であれば，バッテリー駆動のドローンでも代用可能である。しかし，本研究の最終目標は，より大きな面積の連続的な洗浄であるため，有線給電給水放水の開発を目標としており，本研究の成果は，供給ポートを移動させ，より大きな面積をカバーすることができると考えている。

2. 連続放水ドローンの目標設定

2-1　放水面積の目標設定

ソーラーパネル清掃に活用できる連続放水ドローンの開発に当たり，最初に目標となる放水面積を決定する。**図 1** は，機体重量と放水面積の関係を示しており，横軸は放水を行う機体の重量 kg，縦軸は放水面積 m^2 であり，マーカーの色で機体のタイプ，形で駆動方式を表している。なお，水 1 L でソーラーパネルを清掃することができる面積は，国内大手メーカ 4 社のスペックをもとに 0.6 m^2 として算出している [16-19]。バッテリー駆動のドローンから放水するタイプ（▲印）では，水をタンクに貯蔵するため，ドローンの重量は重くなり，放水面積は小さい [20-21]。また，ドローンではないがソーラーパネル清掃ロボットである Resola（▲印）では，飛行する必要がないため，比較的重量が大きくなるが，広い範囲（100 m^2）を清掃できる。一方，**図 1** の左端下は，著者らが以前試作した連続放水ドローン [22]（●印）であり，水を連続供給するホースを接続しており，タンクで水を持ち運ぶ必要がなく軽量化できる。

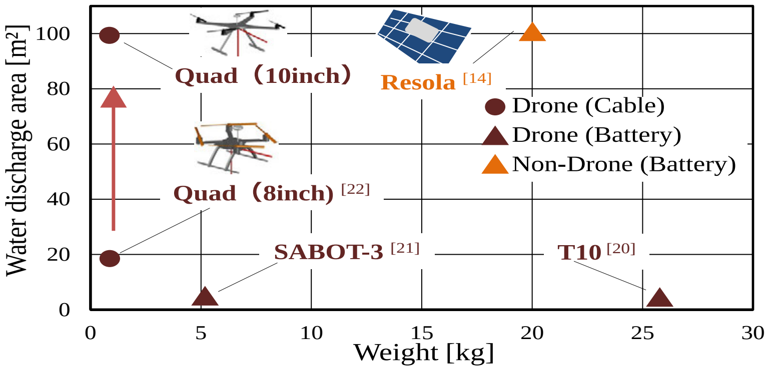


図 1　機体重量と放水面積の関係

そこで，本研究ではこの試作機をベースとして，ソーラーパネル清掃ロボットと同等の 100 m^2 まで，放水面積を拡大することを目標にした。なお，連続放水ドローンの場合，垂直上向きの飛行時に最大負荷がかかるため，本研究では，最も条件の厳しい垂直壁への放水をターゲットにした。

2-2　目標の放水面積を満たす移動距離の設定

前節で決定した放水面積 100 m^2 を達成する飛行高度 H_p と右移動距離 R の目標設定を本節で行う。**図 2** に，供給ポートを起点にしたドローンにかかる荷重の概要を示す。電力と水を常に連続供給するケーブルとホースを，供給ポートからドローンに接続して飛行させる方式である。供給ポートを起点にしたドローンの垂直方向にかかる重量 P_1 は，ホースの密度 ρ_t と水の密度 ρ_w と有線の密度 ρ_c の和に，重力加速度 g を乗して，供給ポートからの高さ H_p まで積分して，式 (1) のように表すことができる。

$$P_1 = \int_0^{H_p}(\rho_t + \rho_w + \rho_c)gdh \tag{1}$$

この重量 P_1 をドローンが荷重 P_D として支えており，式 (2) のようになる。

$$P_1 = P_D \tag{2}$$

次に，ドローンの水平方向にかかる重量 P_2 は，ホースの密度 ρ_t と水の密度 ρ_w と有線の密度 ρ_c の和に，重力加速度 g を乗して，右移動距離 R まで積分して，式 (3) のように表すことができる。

$$P_2 = \int_0^{R}(\rho_t + \rho_w + \rho_c)gdr \tag{3}$$

この時，ドローンの水平方向にかかる重量 P_2 は，ドローンが支える P_D と供給ポート P_p でそれぞれ等分に負担しているため，式 (4) のようになる。

$$P_2 = P_D + P_p = 2P_D \tag{4}$$

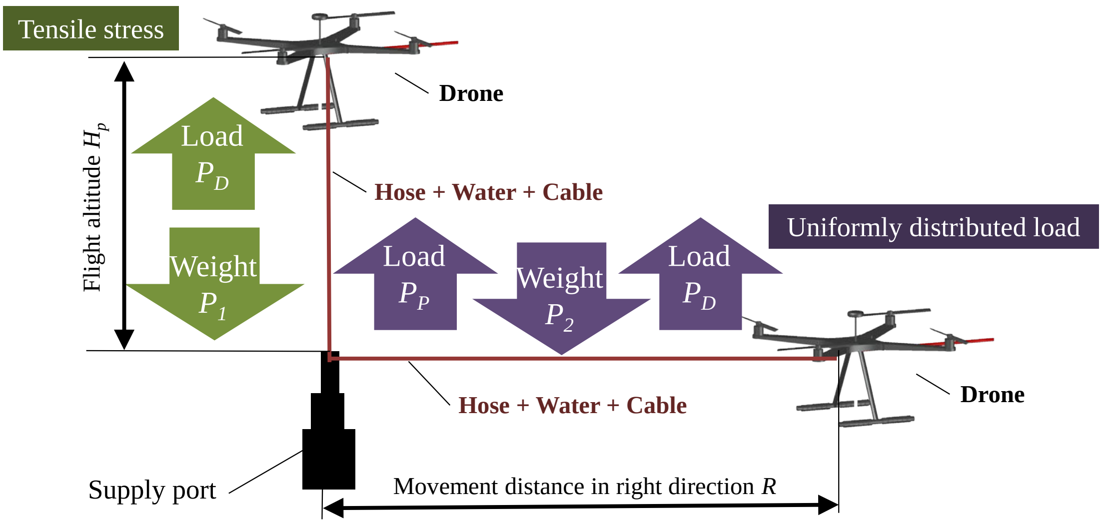


図 2　供給ポートを起点にしたドローンにかかる荷重の概要

式 (4) に式 (2) を代入して，整理すると式 (5) になる。

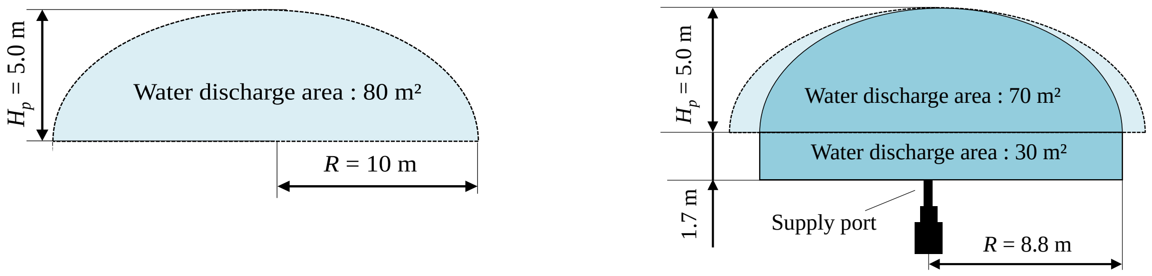
$$2P_1 = P_2 \tag{5}$$

本研究のドローンは，ケーブルとホースによって拘束されているため，移動距離によってドローンにかかる荷重が変化する環境では，飛行距離は荷重に反比例する。つまり式（5）を距離に変換すると，式（6）になり，右移動距離は飛行高度の 2 倍の距離を飛行できることを示している。

$$R = 2H_\mathrm{p} \tag{6}$$

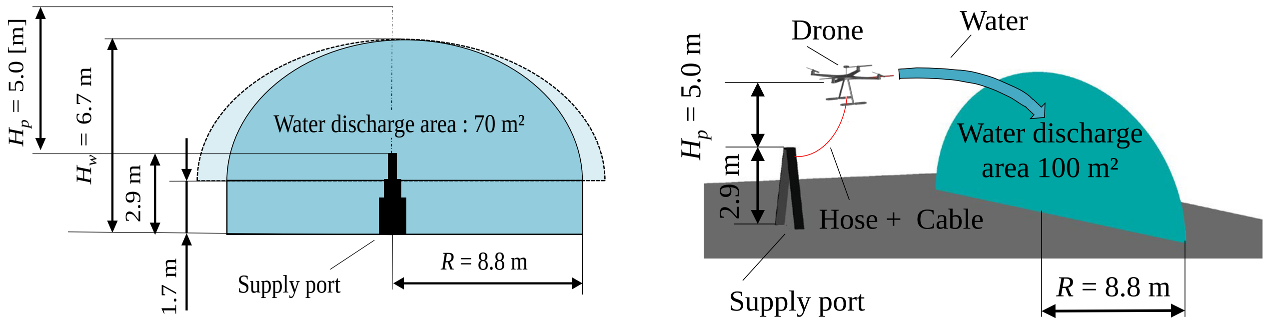
次に，具体的な移動距離の算出を行う。本研究では，通常の水道流量である 0.05 L/s，ホースは内径 4 mm，外径 6 mm，材質は塩化ビニル樹脂製，電源ケーブルは直径 3.5 mm のものを使用することにした。**図 3** に放水面積の算出プロセスを示す。**図 3（a）**は，供給ポート無しの放水面積を表している。実験場の横幅が 11 m のため，ドローンを安全に飛行させることを考慮して，右移動距離を最大 10 m と設定した。また，式（6）より右移動距離 10 m の時，飛行高度 $H_\mathrm{p} = 5.0$ m となり，この時の面積は長軸 10 m，短軸 5 m の楕円の面積の半分になるので，約 80 m^2 と算出できる。しかし，ドローンが水平飛行中には，ケーブルとホースのたわみ，供給ポートの活用による高さ方向のアシスト，および重力の影響で落下する放水軌跡の 3 点を考慮して，目標の放水面積 100 m^2 を満たす仕様を算出する必要がある。

そこで，**図 3（b）**は，ケーブルとホースのたわみ，供給ポートの活用による高さ方向のアシストの上記 2 点を考慮して，放水面積を算出した場合である。さらに，**図 3（c）**は，重力の影響による放水軌跡も追加して，上記 3 点を考慮して放水面積を算出した場合である。なお，**図 3（d）**は，上記 3 点を考慮した**図 3（c）**での放水飛行実験の 3 次元概要図となる。以下に，**図 3（b）～（d）**の詳細を，順番に説明する。



(a) 供給ポート無しの放水面積

(b) ケーブルとホースのたわみを考慮し供給ポートを活用した場合の放水面積



(c) ケーブルとホースのたわみと放水軌跡を考慮し供給ポートを活用した場合の放水面積

(d) 放水飛行実験の 3 次元概要図

図 3　放水面積の算出プロセス

ここでは，**図 3（b）**に示したケーブルとホースのたわみと供給ポートの活用による高さ方向のアシストの 2 点を考慮した放水面積の算出について説明する。**図 4** に，ケーブルとホースのたわみ（以下，「ケーブル類」という）のたわみと右移動距離 R を示す。供給ポートから上方向に飛行する場合は，ケーブル類な

どのたわみはほぼゼロになるが，横方向に移動する場合は，重力によってたわみが生じる。ドローンの右移動距離を R，ケーブル類のたわみの長さを D_h，たわみ角度を θ，1 m あたりの重量を W_h，張力を T_h，たわみが生じたケーブル類の実長を L_h とする。

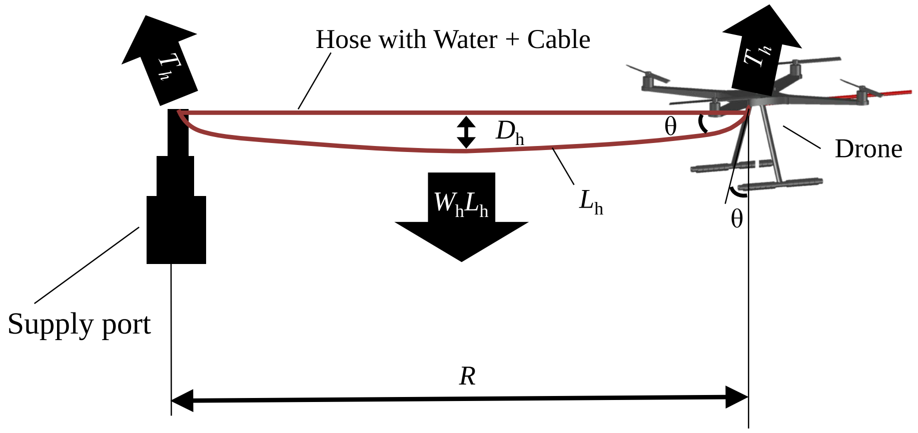


図 4　ケーブルとホース（ケーブル類）のたわみと右移動距離 R の関係

最初に，ケーブル類とドローン，および供給ポートにかかる力を，水平方向と垂直方向に分ける。ここで，水平方向の力は，ドローンと供給ポートでそれぞれ打ち消し合うため，垂直方向のみを考えれば良いことになる。垂直下方向の力は，ケーブル類の重量であり，1 m あたりの重量 W_h とたわみが生じたケーブル類の実長 L_h の積になる。また，垂直上方向の力は，ケーブル類の張力 T_h と $\cos\theta$ の積になり，ドローンと供給ポートの 2 箇所で支持しているため，$2T_\mathrm{h}\cos\theta$ となる。ここで，たわみ角度 θ が微小の場合には，テイラー展開より，$2T_\mathrm{h}\cos\theta = 2T_\mathrm{h}$ と近似できるため，ケーブル類の張力 T_h は，式（7）のように表される。

$$T_h = \frac{W_h L_h}{2} \tag{7}$$

次に，たわみの長さ D_h とドローンの右移動距離 R は，懸垂曲線の関係式 [23] により，ケーブル類の 1 m あたりの重量 W_h，張力 T_h，および実長 L_h を使うと，それぞれ式（8），および式（9）のように求められる。

$$D_h = \frac{W_h R^2}{8T_h} \tag{8}$$

$$3R^2 - 3L_\mathrm{h}R + 8D_\mathrm{h}^2 = 0 \tag{9}$$

ここで，ドローンの右移動距離 R を求めるために，式（8）を式（9）に代入する必要があり，式（10）に示すような 4 次方程式を解くことにより，求めることができる。

$$W_\mathrm{h}^2R^4 + 24T_h^2R^2 - 24T_h^2L_\mathrm{h}R = 0 \tag{10}$$

次に，式（10）より，ドローンの右移動距離 R の具体的な値を算出するために，まず，ケーブル類にかかる水平方向の張力 T_h を式（7）より求める。式（7）中のケーブル類の 1 m あたりの重量 W_h は，**表 1** に示すように，1 m あたりのホースと内部に満たされる水，および電源ケーブルの重量の和となっている。1 m あたりのホースは，前述したホースの内径 4 mm，外径 6 mm，材質は塩化ビニル樹脂製から 40 g となる。

さらに，内径 4 mm に満たされている水の重量 W_W は 13 g となる。電源ケーブルは直径 3.5 mm でプラスとマイナスの 2 本あるので 65 g となる。これらより，1 m あたりのホースと内部に満たされる水，およびケーブルの重量の和は $W_h = 118$ g となる。従って，ケーブル類にかかる張力 T_h は，式 (7) に上記で求めたケーブル類の 1 m あたりの重量 $W_h = 118$ g と，実長 $L_h = 10$ m を代入して，$T_h = 590$ g となる。次に，式 (10) より，ドローンの右移動距離 R を求める。式 (7) で求めた張力 $T_h = 590$ g とケーブルの 1 m あたりの重量 $W_h = 118$ g，実長 $L_h = 10$ m を式 (10) に代入すると，ドローンの右移動距離は $R = 8.8$ m となる。

ここで，**図 3 (b)** に示すように，ドローンの右移動距離 $R = 8.8$ m を楕円の長軸，**図 3 (a)** より求めた飛行高度 $H_p = 5.0$ m を楕円の短軸とすると，半楕円の面積は，約 70 m^2 となり，目標の放水面積である 100 m^2 に届かない。そのため，高さが可変の供給ポートを利用することによって，楕円の放水面積の下に長方形の放水面積が増やす方法を考案した。すなわち，長方形の高さが 1.7 m の場合，横幅が $2R$ である 17.6 m のため，長方形の面積は約 30 m^2 となり，この面積を上側の半楕円の面積に追加すると，100 m^2 の放水面積を達成できることになる。ここまでが，ケーブル類のたわみと供給ポートの活用による高さ方向のアシストの 2 点を考慮した放水面積の算出である。

しかしながら，実際の放水飛行時には，**図 3 (c)** に示したように，重力の影響による放水軌跡も考慮して，放水面積を算出する必要がある。その詳細を，**図 5** を用いて説明する。ドローンを安全に飛行させるためには，壁から L_w 離して飛行させる必要がある。そのため，ドローンからの放水は，水平に壁にたどり着くのではなく，放物線を描き，ドローンの飛行高度 H_p に対して，H_d だけ降下することになる。

表 1　ケーブル類 1 m あたりの重量

Hose W_T [g]	40
Water W_W [g]	13
Cable W_C [g]	65
Total $W_h = W_t + W_w + W_c$ [g]	118

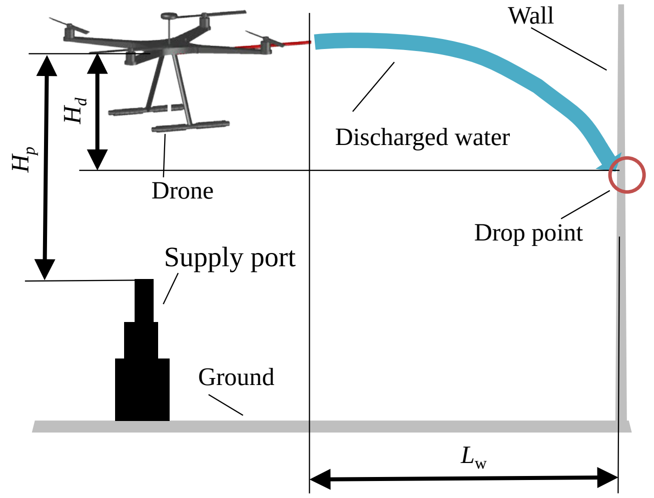


図 5　重力の影響による放水軌跡

ここで，H_d を算出するためにまず，放水流速 V_w を求める。放水流量 Q_w とホースの断面積 A_w とすると，流体力学の流量と速度の関係式より，放水流速 V_w は式 (11) のように求められる。

$$V_w = \frac{Q_w}{A_w} \tag{11}$$

次に，飛行高度と放水高度との差 H_d は，式 (11) で求めた放水流速 V_w と放水点と壁との距離 L_w，および重力加速度 g から，物体落下の運動方程式より，式 (12) で求めることができる。

$$H_d = \frac{g}{2}\left(\frac{L_w}{V_w}\right)^2 \tag{12}$$

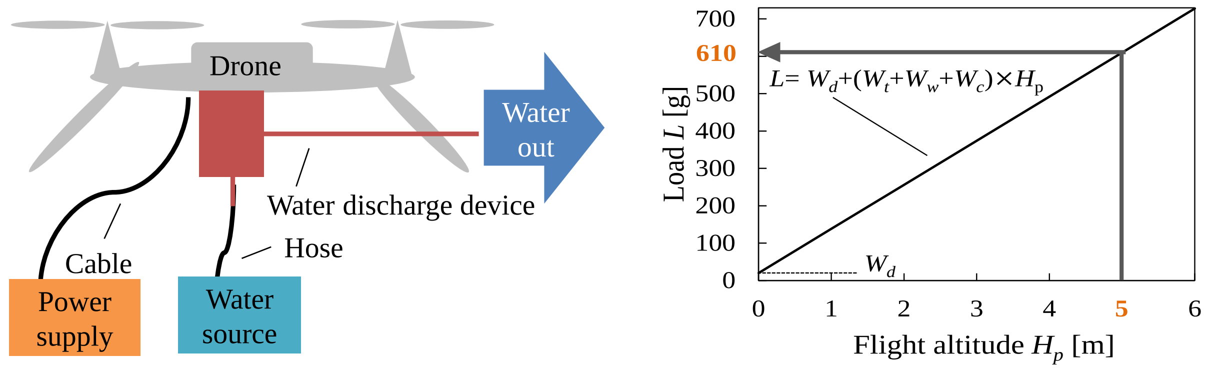
ここで，式（11）と式（12）を使用して，H_{d} の具体的な値を算出する。まず，放水流速 V_{w} は，使用した流量計（GARDENA 9188-U）の放水流量 $Q_{\mathrm{w}} = 0.05$ L/s，ホースの断面積 $A_{\mathrm{w}} = 13$ mm^2（ホース内径：4 mm）から，式（11）より $V_{\mathrm{w}} = 4.0$ m/s と算出できる。なお，放水流速 V_{w} は，ドローンの高度による水道圧力変化の影響を受ける。そのため，水道圧力を圧力計（SANEI R93S）にて計測した結果，平均値は 0.6 MPa，放水高さ（0～5 m）による圧力変化は，±1.7% と微小であったため，今回は水道圧力の影響による放水流速 V_{w} の変動は無視できると考えている。また，供給ポートでの加圧は行っていない。次に，$V_{\mathrm{w}} = 4.0$ m/s，放水点と壁との距離 $L_{\mathrm{w}} = 2$ m，および重力加速度 $g = 9.8$ m/s^2 から，式（12）より飛行高度と放水高度との差 H_{d} は，1.2 m と算出できる。この結果から，供給ポートの高さが 1.2 m 未満の場合には，2 m 離れた壁に水が届かない。そのため，供給ポートの最小高さを 1.2 m に決定できる。さらに，**図 3（b）**に示したように，長方形の高さが 1.7 m 必要なため，供給ポートの最大高さは，1.2 + 1.7 = 2.9 m に決定した。

次に，放水飛行実験の 3 次元概要図を**図 3（d）**に示す。高さ可変の供給ポートから，ケーブル類をドローンに接続し，壁に向かって放水を行う実験である。**図 3（a）**に示したように供給ポートからの飛行高度は $H_{\mathrm{p}} = 5.0$ m，**図 3（b）**に示したように右移動距離は $R = 8.8$ m，**図 3（c）**に示したように供給ポートの高さを 1.2 m～2.9 m にすることによって，目標の放水面積 100 m^2 を達成できる見通しとなった。

2-3　目標の移動距離を満たすドローンのペイロードの要求仕様

次に，目標の移動距離を満たすドローンのペイロード P_{d} の要求仕様を決定する。**図 6** に連続放水ドローンの構成，および飛行高度と荷重の関係を示す。**図 6（a）**は，有線給電給水装置を取り付けたドローンの構成を示している。ドローンの本体以外にかかる荷重 L は，放水装置 W_{d}，および高さ H_{p} によって変化する 3 種類の荷重であるホース W_{t}，ホースの内部に満たされている水 W_{w}，有線 W_{c} の和であり，式（13）および**図 6（b）**のように表される。

$$L = W_{\mathrm{d}} + (W_{\mathrm{t}} + W_{\mathrm{w}} + W_{\mathrm{c}}) \times H_{\mathrm{p}} \tag{13}$$



(a) 有線給電給水装置を取り付けたドローンの構成　**(b) 飛行高度と荷重の関係**

図 6　連続放水ドローンの構成および飛行高度と荷重の関係

ここで，前述した**表 1** に示した値を用いて，飛行高度 $H_{\mathrm{p}} = 5.0$ m のときにドローンにかかる荷重の内訳を示したものが**表 2** である。飛行高度 $H_{\mathrm{p}} = 5.0$ m 時にドローンにかかる荷重の内訳は，放水装置 $W_{\mathrm{d}} = 20$ g，ホース $W_{\mathrm{t}} = 200$ g，ホースの内部に満たされている水 $W_{\mathrm{w}} = 65$ g，有線 $W_{\mathrm{c}} = 325$ g の合計 610 g となる。

表 2　飛行高度 5.0 m 時にドローンにかかる荷重の内訳

Water discharge device W_{D} [g]	Hose W_{T} [g]	Water W_{W} [g]	Cable W_{C} [g]	Total L [g]
20	200	65	325	610

3. 連続放水ドローンの設計

3–1　ドローンの静止推力と消費電力の算出

2–3 節で算出した 610 g 以上のペイロード P_d と既定の消費電力の条件を満たすドローンを，下記のように選定した。まず，式（14）と式（15）から，静止推力 T と消費電力 E を算出した［24］。

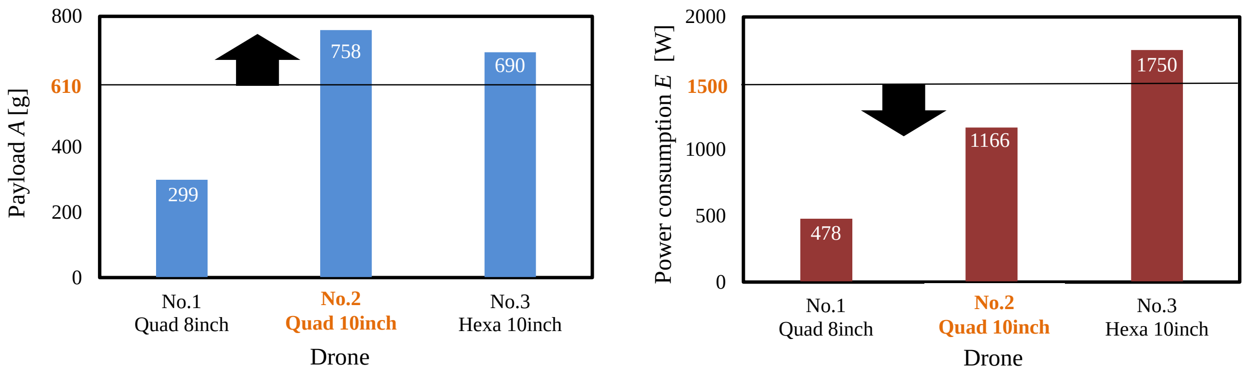
$$T=\left(\frac{D}{10}\right)^3\times\left(\frac{P}{10}\right)\times\left(\frac{N}{1000}\right)^2\times M\times 25 \tag{14}$$

$$E=\left(\frac{D}{10}\right)^4\times\left(\frac{P}{10}\right)\times\left(\frac{N}{1000}\right)^3\times M\times 3.0 \tag{15}$$

ここで，D はプロペラ直径，P はピッチ，N は回転数，M はモーター個数，および末尾の数字は実験により求めた定数である。プロペラ直径を $D=8$ または 10 inch，ピッチを $P=4.5$ inch，回転数を $N=6000$ rpm，モーター個数が 4 個のクアッド，または 6 個のヘキサとして，3 パターンのドローンの性能をまとめたものが**表 3** である。ここで，ペイロード P_d は，静止推力 T とドローンの重量 W の差で算出できる。さらに，**表 3** の結果を棒グラフで整理したものが**図 7** である。**図 7（a）**から要求するペイロード $P_d=610$ g を上回っているドローンは，No.2 と 3 であることがわかる。一方，**図 7（b）**からコンセントの最大許容電力量である 1500 W よりも消費電力が下回っているドローンは，No.1 と 2 である。以上の結果から，ペイロード P_d と消費電力 E の両方を同時に満たしているドローンは，プロペラ直径 D が 10 inch のクアッドである No.2 であるため，本研究ではこれを選定した。

表 3　ドローンのスペック

No.	Drone Type	Diameter of propeller D [inch]	Static thrust T [g]	Power consumption E [W]	Weight of drone W [g]	Payload $P_d=T-W$ [g]
1	Quad	8	829	478	530	299
2	Quad	10	1620	1166	862	758
3	Hexa	10	2430	1750	1740	690



(a)　ペイロード P_d　　**(b)**　最大消費電力 E

図 7　ドローンのペイロード P_d と最大消費電力 E

3–2　開発したドローンと供給ポートおよび使用する放水装置と電源

前節のドローンの静止推力と消費電力の算出結果に基づき，ペイロードと消費電力の要求仕様を満たすように開発したドローンと供給ポートのスペックを**表 4** に示す。ドローンのタイプはプロペラが 4 つある

クアッドで，サイズ 340×340×270 mm，重量 862 g，プロペラ直径 10 inch，プロペラピッチ 4.5 inch，プロペラ回転数 6000 rpm，フライトコントローラーは，DJI 社製 naza m LITE を使用した。**図 8** に，供給ポートと離着陸部に乗るドローンの概要図を示す。供給ポートは上下に伸縮可能な台を使用し，サイズ 0.7×1.3×2.0 m，上方にある離着陸部の面積は 0.9×0.6 m，重量は 12.3 kg となる。また，開発したドローンの写真を**図 9** に示す。要求仕様を満たすパーツを組み合わせ，ドローンの進行方向に放水装置を装着している。

表 4　開発したドローンと供給ポートのスペック

Drone		Supply port	
Type	Quad	Size（W×D×H）［m］	0.7×1.3×2.9
Size（W×D×H）［mm］	340×340×270	Landing parts（W×D）［m］	0.9×0.6
Weight［g］	862	Weight［kg］	12.3
Diameter of propeller［inch］	10	Extendable height［m］	1.2～2.9
Pitch of propeller［inch］	4.5	Material of supply port	Aluminum
Rotation speed of propeller［rpm］	6000	Material of landing parts	Acrylic
Flight Controller	DJI naza m LITE	–	–

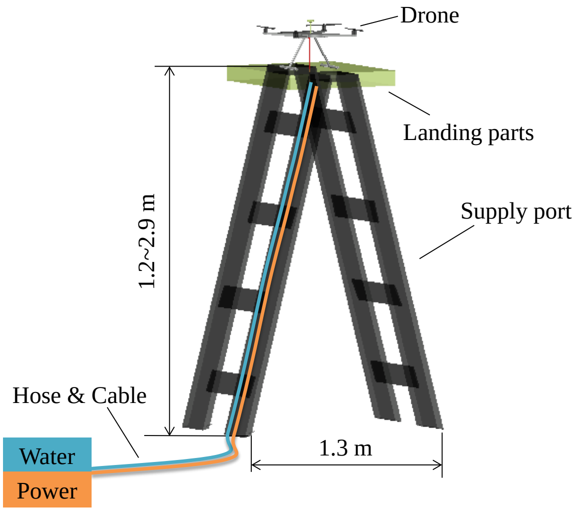


図 8　供給ポートと離着陸部に乗るドローンの概要図

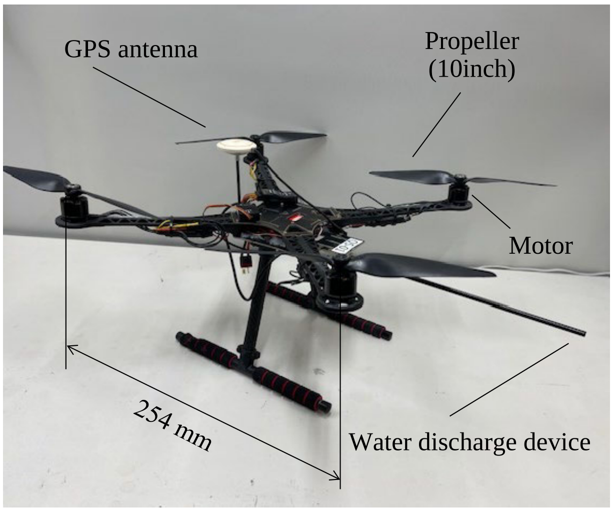


図 9　開発したドローンの写真

次に，選定したドローンに使用する放水装置の 3 次元 CAD（Computer Aided Design）を**図 10** に示す。放水装置は，T 字ジョイントと軽量カーボンパイプから構成され，その接続は，漏水防止用の熱圧縮チューブで固定し，重量は 20 g にした。本実験で使用した放水装置と電源のスペックを**表 5** に示す。電源（MEISHILE S-1200-12）は出力電圧が 12 V，最大出力電流が 100 A で，最大出力が 1200 W のものを使用した。

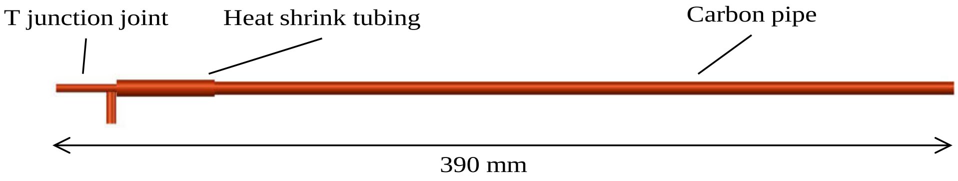


図 10　放水装置の概要図

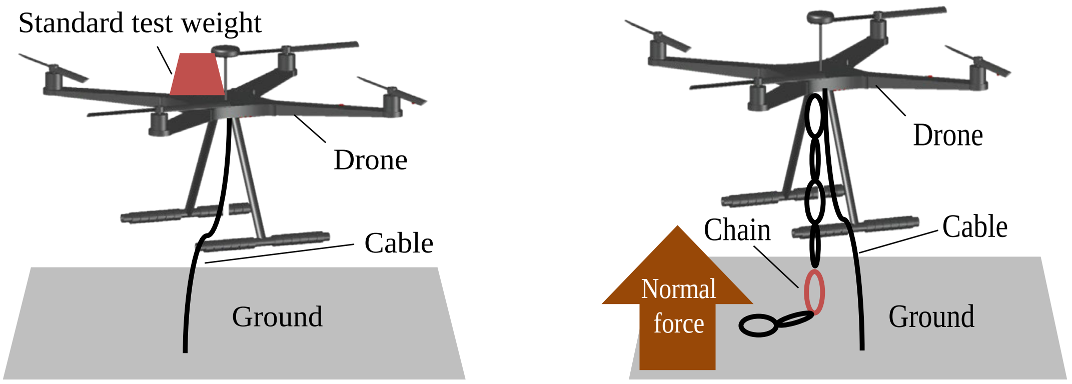
表 5　放水装置と電源のスペック

Water discharge device		Power supply	
Weight［g］	20	Input voltage［V］	100
Length［mm］	390	output voltage［V］	12
Inside diameter of pipe［mm］	4	Maximum supply current［A］	100

4. 連続放水ドローンの飛行検証実験

4-1　ペイロード検証実験

「飛行高度によりホースの長さとその中の水の荷重が変化する」実環境を模擬したドローンのペイロード検証実験を実施するため，重りとして飛行高度に比例して荷重がかかる「チェーン」を使用した。**図 11** に，ペイロード検証実験の方法を示す。**図 11（a）**は，高度によって荷重が変化しない非連続荷重である「分銅」を用いた実験であり，この時のペイロード P_{d} は 550 g であった。一方，**図 11（b）**は，実環境に近い実験として，チェーンをドローンから垂らし，飛行高度が最大になった時，浮いていて最も地面に近いチェーン（**図 11（b）**の赤色）を記録した。なお，実験に使用したチェーンは，重量が異なる 3 種類（3.36 g，7.04 g，12.34 g）であり，**表 6** にその結果を示す。浮いているチェーンの重量からペイロード P_{d} を算出し，3 種類チェーンの平均値を求めると，開発したドローンのペイロード P_{d} は 690 g であることがわかった。なお，分銅とチェーンでペイロード P_{d} の結果に差異が出た理由は，分銅は荷重がそのままドローンにかかるのに対して，チェーンは**図 11（b）**に示すように片側の端点が地面と接しているおり，矢印のように垂直上向きの抗力が働き，その分のアシストを受けたためである。



(a)　非連続荷重（分銅）　　(b)　連続荷重（チェーン）

図 11　ペイロード検証実験の方法

表 6　有線接続によるペイロード検証実験の結果

Standard test weight［g］	Chain（3.36）［g］	Chain（7.04）［g］	Chain（12.34）［g］
550	702	676	691
–	Average：690		

4-2　放水飛行実験

製作した放水装置をクアッドドローンに固定して行った放水飛行実験の概要を**図 12** に示す。左右方向の移動距離は等しいので，代表して右移動距離 R と放水高度 H_{w} の 2 つの項目（**図 12** の枠線内）を計測した。なお，本実験では，ケーブル類を束ねた可変の供給ポートとして，高さ可変の脚立を改良し，高さ 1.2 ～

2.9 m に設置するとともに，上部に離着陸部を装着した。また，本実験環境下では GNSS（Global Navigation Satellite System）が使用できないため，ドローンの位置制御のみを行う ATTI（Attitude）モードに設定した。その際，水の反力で放水方向と反対の反力や，水圧がかかったホースの重みによってドローンの位置が不安定になるため，手動によって打ち消す方向に制御するいわゆる「フレア操作」を行った。

図 13 に，重力の影響による放水の軌道の写真を示す。ドローンを安全に飛行させるために壁から 2.0 m 離して飛行させると，飛行高度と壁面への放水点には 1.2 m の差があることが分かる。

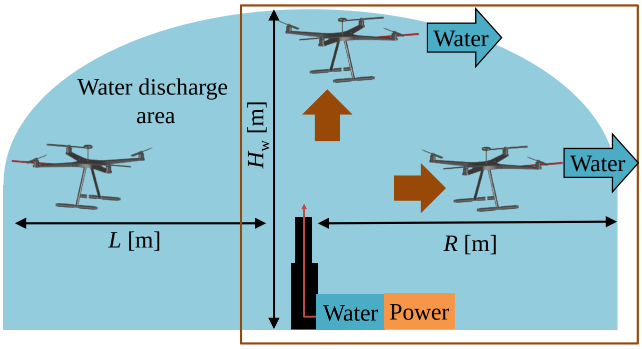


図 12　放水飛行実験の概要

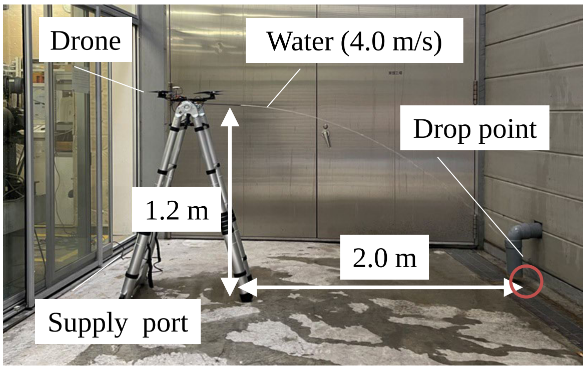
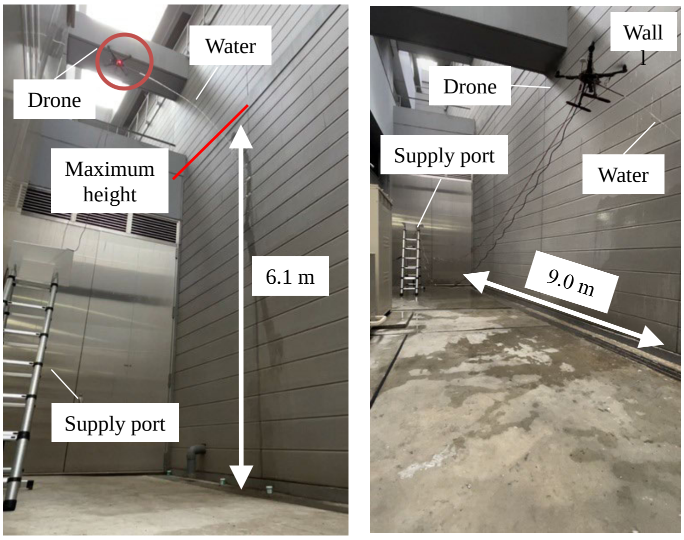


図 13　重力の影響による放水軌道

図 14 は，放水飛行実験（供給ポートの高さ = 2 m）の写真である。**図 14（a）** は，放水高度 H_w を示した写真であり，供給ポートの高さ = 2 m の場合，放水高度 $H_w = 6.1$ m であることを確認した。一方，**図 14（b）** は，ドローンの右移動距離 R を示した写真であり，9.0 m まで飛行できることを確認した。



(a)　放水高度 H_W　**(a)　横移動距離 R**

図 14　放水飛行実験の写真（供給ポートの高さ = 2 m）

表 7　放水飛行実験の結果

Supply port [m]	H_w [m]	R [m]
2.9	6.9	8.8
2.0	6.1	9.0
1.2	5.4	8.9

表 7 に，放水飛行実験の結果をまとめたものを示す。供給ポートの高さを 3 段階（1.2 m，2.0 m，2.9 m）に変えた時の放水高度 H_w と，右移動距離 R をそれぞれ 3 回ずつ計測し，その平均値をまとめた。放水飛行高度に関しては，目標値の 6.7 m より 0.2 m 高い 6.9 m となり，右移動距離 R に関しては平均して 8.9 m 飛行しており，目標値の 8.8 m とほぼ同じ結果となった。以上の結果から，放水面積は 103 m^2 と算出でき，目標としていた放水面積 100 m^2 とほぼ同等になることを確認できた。

5. 考　　察

本研究では，連続放水ドローンによる放水面積の拡大を目指してきた。有線接続により連続放水する場合，垂直上向きの飛行時に最大負荷がかかるため，本研究では，最も条件の厳しい垂直壁をターゲットに開発を進めてきた。一方，実際のソーラーパネルの設置角度は30° 程度が多く，本研究の垂直の壁よりもペイロードが軽くなるため，より放水面積拡大が見込まれると考える。また，ソーラーパネルの設置角度に合わせて，放水角度を最適化し，同じ流量でより多くの汚れを落とすことも考えている。さらに，ソーラーパネルの洗浄度を，画像処理を用いて比較し，数値化して行く開発につなげていく予定である。

6. ま　と　め

本研究では，ドローンの適用範囲拡大の一環として，連続放水の実現を目指した。CONOPSと呼ばれる運用概念を明確にし，その実現に必要十分な性能を有するドローンをCONOPSの範囲内に限定して運用する航空運航の安全管理の在り方を太陽光パネルの放水洗浄という具体例を用いてその安全管理設計プロセスの一部を示した。具体的には，バッテリーの代わりに電源ケーブルによる連続給電，タンクの代わりにホースによる連続給水，および電源ケーブルとホースを束ねた高さが可変の供給ポートも併用する「有線給電給水」方式の開発を行い，以下の結論を得た。

1. 連続放水ドローンの目標設定では，ソーラーパネル洗浄ロボットと同等の放水面積100 m^2 とした。その内訳として，高さ1.2～2.9 mまで可変の供給ポートを設置し，左右の対称性から，供給ポートからの飛行高度5.0 m，右移動距離8.8 m飛行することによって，目標の放水面積を達成できることを算出した。
2. 連続放水ドローンの設計では，目標の移動方向からドローンにかかる荷重を算出し，飛行高度5.0 mと右移動距離8.8 mの場合に最大610 gの荷重がかかることを求め，その要求を満たすことのできるドローンとして，プロペラ直径10 inch，プロペラピッチ4.5 inch，プロペラ回転数6000 rpmのクアッドドローンを開発した。
3. 連続放水ドローンの飛行検証実験では，ドローンのペイロード性能評価を行い，その結果として設計仕様の610 g以上の690 gということを実験から確認した。最後に，目標としていた放水面積100 m^2 とほぼ同等の103 m^2 の領域を放水できることを実験から確認した。

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2023年3月に国士舘大学理工学部卒業とともに，日本機械学会畠山賞受賞。同年4月同大学大学院工学研究科機械工学専攻に進学。Technical Journal of Advanced Mobility ポスターセッション in Japan Drone 2023で発表。現在，連続放水可能なドローンの開発を目標に，流体力学的観点からソーラーパネル洗浄を行うドローンの開発を行っている。

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米国での小型無人航空機法制度の変遷

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小型無人航空機（sUAS）の巨大市場である米国において，Part108と呼ばれる新制度が導入されようとしている。新たな制度が制定されるまでの，これまでのsUAS法制度の変遷を概観することで，米国航空界においてsUASというイノベーションが法制度化されるプロセスや，業界と航空当局との関係，また，自治体におけるsUASの捉え方，災害対応や，安全保障案件などを分析したい。

Keywords: sUAS，米国法制度，ドローン，無人航空機

Changes in the legal system for small unmanned aircraft systems in the United States

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In the United States, which has a huge market for small unmanned aircraft systems（sUAS）, the new act called Part 108 is planning to be introduced. By looking at the changes in the sUAS legal system up to the establishment of the new system, we would like to analyze the process of institutionalizing the innovation of sUAS in the U.S. aviation industry, the relationship between the industry and aviation authorities, the way local government's view sUAS, disaster response, and security requirements.

Keywords: sUAS, United States' legal law, drone, unmanned aircraft systems

1. はじめに

無人航空機システム（UAS, Unmanned Aircraft Systems）は，特に民間利用においては航空法における新たな制度の導入を求めた。ここでは，小型無人航空機システム（sUAS, small UAS）における米国での制度の変遷に関して検討を行う。その理由は，米国が中心となる北米はsUASサービス市場で世界の3割を超える巨大な市場［1,2］であるとともに，航空機の特に安全制度に関して世界をリードしていると考えられるからである。米国において，sUASの目視外飛行を制度化する新たな制度Part108が導入されようとしている。ここに至るこれまでのsUAS法制度の変遷を概観することで，米国航空界においてsUASというイノベーションが法制度化されるプロセスや，業界と航空当局との関係などを分析したい。

sUASは低高度空域での様々な利用分野があり，航空法以外に関連する法令があり，また，航空法が連邦規則であるのに対して，州等の自治体での法令との関連がある。ここでは，米国での航空法を中心に扱うが，災害対応や，安全保障やセキュリティ案件のほか，自治体におけるsUASの捉え方に関しても簡単に触れたい。

2. 米国の航空法の概要

2-1　国際法との関連

航空運航のうち，国際民間運航に関しては国連の専門機関ICAO（International Civil Aviation Organization,

国際民間航空機関）におけるシカゴ条約において，航空安全，航空環境に関する標準規格を推奨実施法案SARPs（International Standards and Recommended Practices）と呼ばれるガイドラインと19のAnnex（付属書）において勧告方式[1]にて参加国に求めている。現状のAnnexは，（1）技能証明，（2）航空規則，（3）気象，（4）航空図，（5）計測単位，（6）運航安全，（7）登録，（8）耐空性，（9）空港での出入国，（10）通信装置，（11）交通管制の運用，（12）遭難救助，（13）事故調査，（14）飛行場設計，（15）航空情報収集・伝達の方法，（16）環境保護，（17）航空保安，（18）危険物輸送，（19）安全管理，をカバーしている［3］。

ICAOの制度は国際民間航空を前提とするため，国際運航を行わない航空機に関しては，国際的な標準化は一般にはなされていない。例えば，米国のウルトラライトプレーンやLSA（Light-Sport Aircraft）は，他国では異なる定義となっており，sUASも同様である。

2-2　米国の航空法体系

米国の航空法はICAOのAnnexを基本とし，米国連邦航空局（FAA, Federal Aviation Administration）の規則は，連邦規則集（CFR, Code of Federal Regulations）の航空宇宙分野（タイトル14）のChapter Iが該当し，199のPartに分類され，特定の規則は「14CFR Part XXX」と参照される（以後はPartと記載）。Chapter IはSubchapter A～Nに分かれ，**表1**のようにPart/Sectionから構成される［4］。

3. ICAOのRPAS

UASのうち，国際運航を想定した大型無人機に関しては，ICAOにおいてRPAS（Remotely Piloted Aircraft Systems：遠隔操縦航空機システム）として制度化がなされている［5］。2000年代に入り，UASの利用が拡大し，ICAOはUASの国際民間航空に与える影響にかんして安全性，セキュリティ，規制の課題を議論するため，2007年に無人航空機システム検討会（UASSG：Unmanned Aircraft Systems Study Group）を設置した。

表1　FAAの航空分野の法体系

サブチャプター	Part	項目	Part/Section
A	Part 1	定義と略語	1.1–1.3
	Part 3	一般的な要件	3.1–3.303
	Part 5	安全管理体制	5.1–5.97
B	–	手続き上のルール	11–17
C	–	航空機	21–59
D	–	飛行士	60–68
E	–	領空	71–77
F	–	航空交通および一般運航規則	89–109
G	–	航空会社およびオペレーター：認証と運用	110–139
H	–	学校およびその他の認定機関	140–147
I	–	空港	150–169
J	Part 170	航空交通管制業務及び航行施設の制定・廃止基準	170.1–170.15
	Part 171	非連邦政府のナビゲーション施設	171.1–171.327
K	–	行政規則	183–193
L	Part 194	特別連邦航空規則第120号―パワーリフト：パイロットの認定と訓練；運用要件	194.101–194.402
M	–	［将来使用予定］	–
N	Part 198	戦争危険保険（航空保険）	198.1–198.17
	Part 199	［将来使用予定］	–

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[1] 勧告方式とは加盟国に自国の航空法制度に反映させせることを推奨するもので，193もの国と地域が参加する多様性をかんがみ必ずしも強制するものではないことを意味する。

UASSGはその課題を2011年に資料（Circular328）として公開した。その中で，遠隔操縦航空機システム（RPAS: Remotely Piloted Aircraft Systems）という用語が使用され［6］，2012年にはRPASマニュアルも発行された［7］。

UASSGは2014年にICAOの正式なRPASパネルとして発展的に継承され，RPASに関する基準とSARPsの開発が開始された。具体的には各AnnexにおけるRPASの取り扱いが議論された。2024年の時点で，19のAnnexのうち15の改正がICAO理事会で承認され，RPASの国際運用を可能にする規制の枠組みの基本的な構成要素が整ったとされた［8］。この中で，遠隔操縦士免許，耐空証明，RPASオペレーター証明書，操縦用無線（C2リンク）周波数帯の規定が示された。ICAOの規定は前述のように勧告であり，今後，各国での航空法に取り込まれることで，UASの国際運航開始に向けた準備が整うことになる。

4. FAA sUASの制度

4-1　2016年以前の制度（Part107の発効前）

UASの国際運航は，RPASとしてICAOで国際的な制度化が進められたが，小型のsUASに関しては，ICAOではなく各国での制度化が独自に進められている。米国のsUAS制度は2016年にPart107が施行され大きく変化するが，それまでの状況をここでは整理する。

多くの国がそうであったように，米国においてもsUASは航空法の対応外であり，比較的自由に使用することが可能であった。しかし，2007年にsUASを航空機として扱う政策文書が発行され，sUASの飛行が厳しく管理されるようになった［9］。そこでは，sUASは主に国防省などが使用する公的（Public），商用目的や研究で使用する民間（Civil），ホビーで使用する模型（Model）航空機と分類され，民間でのsUAS利用はホビー目的以外においては厳しく管理されることになった。

こうした中，sUASに関する民間利用のルールを検討するARC[2]（Aviation Rulemaking Committee）がFAAの下に構成され，2009年に答申［10］を公示した。それらのルールが制定されるのは2016年に施行されたPart107を待たねばならなかった。

2012年に連邦議会が可決したFAA近代化改革法（2012FMRA, FAA Modernization and Reform Act of 2012）は，航空管制の大幅な近代化（NextGen）を実現するためにFAAに対して出された改革法であるが，その中に「2015年9月30日までにFAAが民間sUASの使用に関する制度を制定する」ことが求められ，sUASの制度化が大きく加速されることになった［11］。

2012FMRAによりPart107が生まれるまでに，民間sUASの飛行許可をFAAから取得するには実際には2つの方法が存在した。

（I）2012FMRAに記載されたSection333により飛行許可を得る。

（II）公的機関がFAAから飛行許可を得るCOA（Certificate of Authorization）という特別な申請制度を利用して公的機関と連携して飛行させる。

実際には（I）で飛行許可を得ることは容易ではなく，2012FMRAでもSection334で（II）を推奨していた。Section333による飛行はPart107の発効により無くなるが，COAはPart107発効後もCOA（Certificates of Waiver and Authorization）として引き続き適用されている。

2012FMRA以降，sUASの利用促進に向けた施策がFAAにおいてなされ，以下はその代表的なものである。

（I）UASテストサイトプログラム；2012FMRAのSection332（国家空域システム統合）の一環として，FAAは6つのUASテストサイトを指定し，2014年に運用を開始し，その後も継続的に運用が続いている［12］。

（II）UAS Pathfinder Program：sUASの利活用拡大のために，（1）都市部での取材撮影のための目視内

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[2] ARCはFAA長官が認可する業界，有識者，利益団体のメンバーで構成され，目的に応じて設置され，指示された課題への諮問をおこなう。

飛行，（2）農作物観測のための目視外飛行，（3）鉄道レール点検のための目視外飛行，に関する研究プログラムとしてFAAは3事業者を指定した［13］。

（III）UAS Center of Excellence：FAAは，2015年にミシシッピ州立大学を中心とした23の研究機関の共同体ASSURE（Alliance for System of UAS through Research Excellence）を選定した［14］。

4-2　2016年から2018年の制度

FAA近代化改革法（2012FMRA）により，sUASに関する初のFAA規則Part107が2016年より施行され，sUASの民間利用が急速に広がり，飛行安全を実現する新たな制度や，産業振興策が積極的に展開されたのがこの時期である。

（1）Part107の制定

2012FMRAで要請されたsUASの制度は，2015年3月にPart107-Small unmanned aircraft systemsの案として公示され意見募集NPRM[3]ののち，2016年6月に最終案が示され，2016年8月に施行された。また，sUASの登録制度も2015年12月より開始された［15］。

FAAの登録制度は0.55ポンド（約250グラム）を超え，55ポンド（約25キログラム）未満のsUASが対象となり，ホビー用のsUAS登録は，2017年5月の裁判所の命令で無効とされたが，同年12月の国防権限法NDAA[4]により復活している。

Part107自体は，登録されたsUASの民間利用を規定するもので，日中の目視内飛行VLOS（Visual Line of Sight）で，第三者上空の飛行を禁止し，高度は400フィート（約120メートル）未満，管制空域を飛行する際には，管制機関からの許可を求めるなどが規定された。日本の制度と近いが，移動体からの操縦を禁止し，時速100マイル以上の飛行を禁止するなども求めている。こうした制限以外の飛行を行うためには，申請による規則の免除（Waiver）を受けることができ，従来のSection333の制度は廃止された。

（2）Part107ライセンス

sUASの操縦には，16歳以上で，Part107.73で指定された航空知識（空域の分類と運用要件，および小型無人航空機の運用に影響を与える飛行制限，航空気象と小型無人航空機の性能に及ぼす気象の影響，小型無人航空機の荷重と性能，緊急時の手続き，クルーのリソース管理，無線通信の手順，小型無人航空機の性能，薬物とアルコールの生理学的影響，航空の意思決定と判断，空港利用，メンテナンスと飛行前点検の手順，夜間の運行）をFAAが認定した知識センターで三択形式の試験により60問中70％以上合格することが求められる。受験料は175ドルで24カ月で更新（無料）となる。有人機のパイロット資格保有者はオンライントレーニング（無料）を受講し，申請を行う必要がある［16］。ホビー用途では，Part 107　ライセンスは不要であったが，2021年から，レクリエーションUAS安全テスト（TRUST）に合格することが求められた（無料）［17］。

sUASの登録数，Part107ライセンス，TRUST保有者に関しては，2024年8月時点で**表2**のような報告がなされている［18］。機体登録数はホビー用も含まれているが，Part107ライセンス登録数やリモートID発行数は業務用途にほぼ限られていると考えられる。

表2　2024年でのsUAS登録数，ライセンス数，リモートID発行数［18］

sUAS登録数	785,827
Part107ライセンス登録数	388,838
TRUST証明書発行数	852,456
リモートID発行数	390,027

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[3] NPRMはNotice of Proposed Rulemaking（規則提案通知）のことで，政府機関が新たな規則や規制を提案する際に，一般からの意見を募集する公式な通知。

[4] NDAAはNational Defense Authorization Act（国防権限法）のことで，国防総省DODの予算，支出，政策を承認するために毎年制定される。

(3) 2016 年の FAA 拡張，安全およびセキュリティ法 FESSA2016

連邦議会による 2016 年の FAA 延長，安全およびセキュリティ法（FESSA 2016, FAA Extension, Safety, and Security Act of 2016）[19] を契機に，sUAS の FAA による法制度化が大きく進展することになる。

FESSA2016 は空港改善プログラム，パイロットの健康管理プログラム，航空サイバーセキュリティなどの取り組みのほか，sUAS での分野では

・リモート ID 導入の要請
・非常時の特別許可手続きの要請
・空港周辺の無人航空機の検知を目的としたプログラム実施の要請
・NASA と協力した UTM（Unmanned Aircraft System Traffic Management）の調査研究の要請
・重要施設の無人航空機飛行禁止手続きの要請

などが言及され，その後の具体的な制度制定へと繋がった。

こうした連邦議会からの要請に応える形で，2016 年には，FAA の諮問委員会として Drone Advisory Committee（DAC）が設立され，産業界，研究者，技術者等の幅広い構成員によって，全米空域システムへの無人航空機システムの統合にかかる課題について議論が開始された [20]。なお，DAC は，2021 年には，Advanced Air Mobility（AAM）を委員会の焦点に含めるために，Advanced Aviation Advisory Committee（AAAC）に移行された。

また，2008 年に制定された，sUAS に関する民間利用のルールを検討する ARC は，Micro UAS Aviation Rulemaking Committee（MUASARC）として 2016 に再編成され，sUAS への安全要件への適合性証明方法 MOC[5] などが議論されることとなった。FAA は小型機の安全要求（Part23）を民間標準化団体で開発された MOC を積極的に安全審査に取り入れる Performance Based 制度[6] への移行を 2017 年に行っており [21,22]，sUAS の安全審査に関しても 2009 年の ARC において同様な手法を取り入れることが諮問された。Part23 の MOC 開発には民間標準化団体 ASTM International が主体的にかかわっており，UAS の MOC 開発に向けて ASTM 内に UAS に対応する技術委員会 F38 が 2003 に組織されており，F38 が sUAS の MOC 開発を担うことになった [23]。

(4) リモート ID

無人航空機の遠隔からの識別や追尾を可能とするリモート ID が FESSA2016 において要請され，FAA は UAS Identification and Tracking Aviation Rulemaking Committee（UASIDARC）を 2017 に設立し，リモート ID 制度化への準備を開始した。UASIDARC は 2017 年 5 月に案を公示する予定であったが，3 回延期され，同年 12 月に公示された [24]。

その後，FAA は 2019 年 12 月から 60 日間に一般から意見を求め（NPRM），2021 年 1 月に制度の最終案を公示し，リモート ID の制度は同年 4 月より施行された。例外となる機体は，重量が 0.55 ポンド（約 250 グラム）以下，かつホビー用に使用される機体，及び米軍により使用される機体と，広範な要求となるため審議も長引いた。Wi-Fi や Bluetooth での無線発信以外に，規則案では存在したネットワーク型リモート ID は最終案では見送られた。リモート ID の要件には，ASTM F3411-19 が採用されている。

(5) 空港周辺での sUAS 運航管理

空港周辺での sUAS とのニアミスが報道されるようになり，FESSA2016 でも問題視された。FAA は，空港周辺の低高度における sUAS の情報を空港管制に通知し，飛行許可を得るシステム LAANC（Low Altitude

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[5] MOC は Means of Compliance（適合証明方法）のことで，規制や基準を満たすための具体的な方法や手段を指す。

[6] Performance-Based 制度（パフォーマンスベース制度）とは，規定や基準の達成方法を細かく定めるのではなく，達成すべき目標に焦点を当てる制度である。

Authorization and Notification Capability）を開発し，2017年から試験的な運用を開始した。

LAANCは米国の726の空港で使用され，FAAが認証したAirMatrixなど12社のUASサービスプロバイダー（USS）システムが使用され，400フィート未満の空港周辺での飛行承認をほぼリアルタイムで得ることができる。これはPart107ライセンス保有者と，ホビー利用のTRUST保有者が利用できる。ちなみに，400フィート未満でも高度が指定されている場合は，Part107ライセンス保有者のみ空港施設と事前調整することができるとされている［25］。

（6）DroneZone

FAAは機体登録を含む様々なサービスを提供するために，2015年10月にUAS登録タスクフォースを立ち上げ，2015年12月にsUAS登録に備えてWebサイトを立ち上げることを公示した。現在，DoneZoneとしてWebサイトが運用され，空域の認可と免除，運用上の免除，および事故報告の収集と処理が行え，FAAは，UASコミュニティが使用する様々なサービスのためのアクセスポイントを提供するなど，Webサイトを強化することを宣言している［26］。

（7）UAS統合パイロットプログラム

2017年には，第一期トランプ政権による大統領令により，全国における無人航空機の運航に関する将来の連邦ガイドラインや規則決定の参考とするために，民間事業者と行政機関が協力してsUASのパイロットプログラムが立ち上がった［27］。このプログラムは2020年に修了したが，その後，後継のBEYONDプログラム［28］に引き継がれた。

4-3　2019年から2024年の制度

2016年に施行されたPart107により，sUASの民間利用が制度化され，その利用も活発になるが，Part107では個別審査とされた夜間飛行，第三者上空飛行の制度化，およびsUASの物流事業の制度化，また，sUASの型式証明の制度化が進んだのがこの時期である。2018年，連邦議会において2023年までのFAAの活動を承認したFAA再授権法[7] 2018において，sUASに関する重要な政策も承認された。リスクに応じたsUAS安全要求に関してPerformance BasedのMOCの採用を要請するとともに，sUASによる有償の物流事業の制度化や，ホビー用のsUASに関する規制も要請された［29］。これらはFAAによる制度として順次具体化されていった。

（1）Part135によるsUAS物流事業

2018年にWing Aviation LLC（Wing）がオーストラリアなどで実証試験を行った実績をもとにFAAに対して申請したことを契機に，FAAは2019年に，Part135による申請をsUAS事業者に求めた。Part135は，FAAが定める航空運送事業者および運航者に関する規則で，定期便以外の航空運送を行う事業者が対象となり，sUAS事業者も有償の物流事業を行う際にはその申請が求められることとなった。2018FAA再授権法の要請をFAAが制度化したことになる。

sUAS事業者として最初に承認を得たのは，Wingで，2019年4月にFAAから発表された。WingはFAAのUAS統合パイロットプログラムとして，バージニア州ブラックスバーグで商用パッケージ配送を開始する試験を開始，その後，AmazonやUPSも試験的なsUASによる配送を開始した［30,31］。

（2）夜間・第三者上空飛行の規則化

Part107のWaiver申請の多い，夜間・第三者上空飛行に関してFAAは2019年2月に新たな規則案を公示し，意見公募（NPRM）を開始した。2021年1月に意見を取り込んだ新規則（夜間飛行はPart107.29，第三者上空飛行はPart107 Subpart D）を示し，4月より施行となった。

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[7] 再授権法 (Reauthorization Act) とは，特定の法律やプログラムの有効期限が設定されている場合に，その期限を延長し，同時に必要な修正や更新を行うために制定される法律であり，FAAではFAAの運営を維持し，予算と政策を更新するために指示される。

夜間飛行に関しては，Part107 ライセンスに夜間飛行の項目が追加され，衝突防止灯の装備が要求され，第三者上空飛行に関しては，墜落時の人への危害リスクに応じて小型の無人航空機を 4 つのカテゴリーに分類した上で，各カテゴリーに対して要件を設定した。当初の案からは NPRM により，カテゴリー 4 が追加されるとともに，リモート ID に係る要件が追加された。

カテゴリー 1 は，0.55 ポンド（約 250 グラム）以下の小型機で，プロペラガードが必須で，イベント上空ではリモート ID も義務づけられる。カテゴリー 2 と 3 に関しては，墜落時のリスク評価に ASTM F3389 が採用され，FAA による確認が求められた［32］。これまでに承認を得られた機体は，小型ドローンにパラシュートを装着したものと，発泡素材を用いた小型の固定翼機である。カテゴリー 4 は，Part21 による型式証明（後述）を必要とするが，認証を受けた機体はまだ出ていない。

(3) sUAS の型式証明

FAA は sUAS の型式証明を Part21.17（b）による「special class」（有人機の特殊クラス）として扱う。この方針は，次の手順で定められた。2020 年 2 月，FAA が小型無人航空機の型式証明の取り扱いの案を公示し，意見公募手続きを開始し，2020 年 9 月，小型無人航空機の型式証明の取り扱いを決定。その後，2020 年 11 月に，10 種類の小型無人航空機に対し，FAA が個別の安全性基準の案を公示し，意見公募手続きを開始した［33］。

現時点では，測量・警備用と，物流用のそれぞれマルチロータ機が型式証明を取得しているが，第三者上空飛行は認められてはいない。申請者は申請機体の運用コンセプトを規定し，機体レベルでの試験や信頼性を示すことが求められる（D&R 方式）［34］。

(4) FAA の sUAS 目視外飛行 BVLOS（Beyond Visual Line of Sight）

航空規則制定委員会（ARC）はこれまで Part107 の特例（Waiver）として許可された目視外飛行を制度化するために，目視外飛行に関する報告書を 2022 年 2 月に公示した［34］。その主な提言は，以下のとおりである。

- 許容可能なリスクレベルの設定：リスクレベルを小型機やウルトラライト機と同等の無人機まで設定する。
- 運航権の決定：ADS-B[8] を搭載しない小型機はドローン空域に侵入しない。ADS-B を受信したらドローンは回避する。
- 新たなパイロット資格：目視外飛行を行うリモートパイロット資格を新設する。
- 新たな目視外飛行（BVLOS）規則：小型機やウルトラライト機と同等のリスクまでの機体認証制度を制定する。
- 自動化と複数機の同時運航を検討する。
- 運航を支援する第三者サービスプロバイダーに関する規則を制定する。
- 無人航空機の整備・修理に関する基準を制定する。
- 無人航空機運航事業者制度を新設する。
- 上記の提案を制度化した，Part108 を新設する。

(5) FAA 再授権法（2024 年）

2024 年 5 月に告示された FAA 再授権法では，2025 年から 2028 年の FAA における米国航空業界向けの資金と政策が提示された［35］。主な内容は，年間 40 億ドルの空港開発予算，航空管制の近代化，サイバーセキュリティ強化，安全性向上策などが含まれており，sUAS に関しては，**表 3** に主な項目を示すが，目視外飛行における ARC の提言を受け，Part108 の新設を求めている。

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[8] ADS-B は Automatic Dependent Surveillance–Broadcast のことで，放送型自動従属監視のこと。

表3 FAA再授権法2024におけるsUASに関する主な項目

条項	概要
$907：リモートIDの代替コンプライアンス手段	リモートIDで外されたネットワークベースのリモートIDを検討
$908：パート107免除の改善	過去の免除リクエストから収集したデータを活用し，ビッグデータ分析と機械学習を使用するように指示
$910：山火事対応における無人航空機システムの使用	山火事対応における公的機関によるUAS使用計画を策定するよう指示。この計画には，指定されたエリアでの目視外（BVLOS）運用を促進
$915, $916：諮問委員会	先進航空諮問委員会（AAAC）を終了し，無人自律飛行諮問委員会（UAFAC）に置き換えて，無人および自律飛行の運用に関連する政策および技術問題についてFAAに助言
$920：BEYONDプログラムの延長	UAS統合パイロットプログラムの後継であるBEYONDプログラムを延長
$924：UAS自動化に関する包括的計画	自律型UASを国内空域に統合するための包括的な計画を策定
$925：UAS試験場	UAS試験場プログラムを継続することを要求し，管理者が適切とみなす最大2つの新しい試験場を承認
$930：UASの目視外運用	提案された規則制定のBVLOS通知を4か月以内に公開し，通知の公開後16か月以内に最終規則を公開（Part108）
$931：BVLOS許容リスクレベルとリスク評価方法論	BVLOS運用のリスク評価方法論を開発し，その方法論を公表
$934：公海上での運用	他の民間航空当局と協力して，米国の管理下にある飛行情報地域内の公海でのUAS運用を許可するプロセスを確立して実施

5. FAAの緊急時のsUASの扱い

自然災害など緊急時にsUASを飛行させるために，米国ではSGI（Special Governmental Interest）プロセス[9]を使用することができる。これは，FAA再授権法2016を契機に運用に導入された。FAAでは，

・消防：山火事の抑制と緊急警告エリアの監視を含む
・捜索救助
・公的機関の緊急活動
・重要インフラの修復
・災害復旧関連の保険金請求を支援する損害評価
・メディア報道により，重要な情報の一般市民への提供

などを例示している。

SGIプロセスを通して，sUASの飛行免除を取得するには，Part107ライセンスが必要で，Part107の特例（Waiver）または，公共機関であればCOA（Certificates of Waiver and Authorization）として資格を取得しておくことが求められ，緊急時にFAAのシステム運用サポートセンター（SOSC，System Operations Support Center）に電子メールで申請を行うことになる。事前に許可された飛行方法以外の飛行を行う際には，SOSCへの申請時に追加申請し，許可を得る必要があるとされている［36］。

6. sUASの国家安全保障との関係

2015年1月26日早朝，ホワイトハウスの敷地内でsUASの墜落が発見されて以降，sUASがもたらすセキュリティーリスクに関する議論が高まった［37］。国家安全保障上の観点から，2018年に制定された国

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[9] SGIプロセス自体は，国家安全保障や人道的または緊急時対応のために設定された通常の手続きをとらない特別プロセスとして設定されたものである。

土安全保障法の改正である Preventing Emerging Threats Act［38］において，脅威となる無人航空機に対する実力行使等の対処が可能となり，その後実現されるリモート ID の制度化，空港周辺の sUAS の管理（LAANC）などにおいて FAA との調整が図られた。

2019 年の NDAA［39］においては，連保機関での敵対国ドローンおよびその部品の調達・使用が，データのセキュリティ対策，遠隔操作の妨害などサイバーセキュリティ対策の観点から禁止され，国産技術の開発奨励がなされた。こうした規制と国内産業・技術の促進策は，毎年のように強化されている。

セキュリティ対策としては。2019 年の Secure and Trusted Communications Networks Act of 2019（安全で信頼できる通信ネットワーク法）［40］において通信機器やインターネットサービスに関して規制がかけられたが，2024 年 6 月には，sUAS を対象にした Countering CCP Drones Act［41］が下院で可決され，民間利用のドローンも対象とした点が注目され，上院でも可決され法案として成立すると大きな影響が出ることが予想される。

さらに，2025 年 1 月に公示された，商務省の立法案事前公告 Securing the Information and Communications Technology and Services Supply Chain: Unmanned Aircraft Systems（ANPRM 2024-30209）［42］においては，sUAS に関連する ICTS（情報通信技術およびサービス）に関する取引，またはそれに関連する活動で，米国の国家安全保障にリスクをもたらす可能性のあるものについて，一般からの意見を求めた。これも，ドローンの民間利用を対象とし，セキュリティの規制は，連邦機関での sUAS のみならず，民間利用への規制へと広がる動きにある。

7. 州法等との関係

連邦政府のみならず，州および自治体が独自に規制を設ける場合がある。Drone Integration and Zoning Act of 2019［43］として提出された法案は，高度 200 フィート以下の飛行に関して土地所有者の許可を求めることを要求している。高度 200 フィート以上の建造物のある空域は飛行できないとされている。この法案はまだ発行されていないが，州および自治体が独自に sUAS に条例として規制をかける場合がある。それは，飛行高度だけでなく，経路や，機体重量などに自治体特有の条例を課す場合があり，地元住民との対応のために，運行事業者には個別のコンプライアンス対応が求められる［44］。地域による規制の差異は，日本において自治体ごとに規制の在り方を導入する際の参考にもなり，今後の分析が必要といえる。このように，不法侵入，プライバシー，個人情報保護など航空法とは異なる要件で，ドローンが制約を受けることも注目しなくてはいけない。

8. おわりに

米国における小型無人航空機 sUAS の航空安全に関する制度の変遷を整理することで，sUAS というイノベーティブな技術を社会実装する際の制度作りのアプローチを見ることができる。米国では，大統領令や連邦議会での FAA 再授権法などの法令と，FAA の下で招集された専門家や業界団体による ARC 等での委員会答申のもとで，FAA により新たな制度が公示され，NPRM により一般の意見を聴取し最終案を施行させていることが分かる。また，示された安全基準の適合証明方法（MOC）は，民間の標準化団体での検討を FAA が選択する Performance Based 方式がとられ，特に sUAS ではリスクに応じた基準の設定が指向されている。sUAS では安全性のみならず，セキュリティ要件も近年では重視され，ICTS（情報通信技術およびサービス）に関する規制とも深く関係している。そして，新たな制度 Part108 が検討されるなど，制度作りが今なお進行中であることが分かる。

米国と並び，航空制度をリードする欧州では，FAA が現行の航空法の改定をベースに法整備を進めるのに対して，EASA（European Aviation Safety Agency，欧州航空安全機関）の sUAS 制度は，大枠の法律を

最初に定め，段階的に施行を進める方針をとっている［45］。我が国も含め国際的な整合をとることが今後の大きな課題であり，そのためにも各国の法制度を理解することが重要である。本稿が米国の制度を理解するための一助となれば幸いである。

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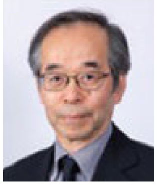

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Proposal of a Drone Accident Analysis Model Based on the SHEL Framework

— Development of the S-SHOELR Model Structured on the SHEL Framework —

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Small unmanned aerial vehicles (drones) are increasingly utilized across various fields, including agriculture, logistics, aerial photography and disaster surveys and management. However, the number of drone-related accidents continues to rise each year, highlighting the need for the establishment of effective safety measures. The lack of systematic analysis of accident causes can be one of the prime reasons for this trend. In this study, we analyzed the current state of drone accidents in Japan using H.F. Hawkins' SHEL model, which is widely used in human-error analysis. Based on the results of the analysis, we developed a new accident analysis model specifically designed for drones, called the S-SHOELR model. The model incorporates the traditional SHEL framework with two additional analysis elements—Safety and Radio wave (communication)—while clearly distinguishing between Operators and Liveware (related personnel). The S-SHOELR model is not only useful for accident analysis but also applicable to risk assessment and operator training, contributing to the safer operation of drones.

Keywords: Drone (UAV), SHEL model, human error, Risk and crisis management

1. Background

Small unmanned aerial vehicles (referred to in this study as multicopters with four or more propellers, hereafter referred to as "drones") have been increasingly utilized in a wide range of fields, including pesticide spraying, power line inspection, cargo transportation, disaster surveys, and aerial photography. In Japan as well, the Roadmap towards the Industrial Revolution in the Sky 2024 [1] outlines prospects for the further utilization of drones, indicating their expected expansion. However, as the use of drones has increased, so has the number of drone-related accidents. According to reports submitted to the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), the number of domestic drone-related accidents and incidents rose from 71 cases in FY2020 (April 1, 2020 – March 31, 2021) [2] to 139 cases in FY2021 (April 1, 2021 – March 31, 2022) [3].

In 2022, Japan's Civil Aeronautics Act was amended to distinguish between "accidents" and "serious incidents" involving unmanned aerial vehicles. Accidents are defined as "cases involving serious injury or death of a person, damage to third-party property, or collision/contact with a manned aircraft," while serious incidents are defined as "cases involving minor injuries, loss of drone control, in-flight fire, or risk of collision/contact with an aircraft" [4]. In the following fiscal year, FY2023, a total of 447 drone-related cases were reported to MLIT [4], of which 86 cases were recognized as either accidents (65 cases) or serious incidents (21 cases). An additional 361 cases were reported, indicating a growing number of drone-related accidents or potentially hazardous situations.

The 2022 amendment to the Civil Aeronautics Act made it mandatory to report accidents and serious incidents involving drones when such events threaten the safety of manned aircraft operations or endanger people or property on the ground or in the water. The purpose of this requirement is to identify the causes of these events and implement measures to prevent recurrence [5]. Although MLIT publishes the reported cases on its website [6], the current data is limited to simple statistical aggregation, and systematic factor analysis has not yet been sufficiently developed.

From a risk and crisis management perspective, it is crucial to analyze past incidents and implement countermeasures based on the PDCA cycle (PLAN: planning, DO: implementation, CHECK: evaluation, ACTION: improvement) [7] in order to prevent future accidents. However, analytical approaches that incorporate the PDCA cycle or systematic accident analysis models specific to drone accidents remain underdeveloped. In the aviation industry, accident analysis incorporating human factors into account has long been established, with approximately 70–80% of aviation accidents attributed to human error [8]. It is therefore highly likely that human error also plays a significant role in drone accidents.

In recent years, human error has increasingly been viewed not as a “cause” but as a “result” arising from organizational and systemic factors [9, 10], prompting further research into analytical methodologies. One of the most prominent frameworks is Edwards’ SHEL model, which categorizes factors into Software (S), Hardware (H), Environment (E), and Liveware (L, referring to personnel involved) [11, 12]. Extensions of the SHEL model have been developed for various fields, such as H.F. Hawkins’ SHEL model, which includes the drone operator as a central Liveware element [12, 13]; the m-SHEL model, which adds Management [12, 14]; the P-mSHELL model, which includes the Patient in medical contexts [12, 15]; and the St-mSHELL model, applied to human error in university administrative operations [10, 12, 16].

Although the SHEL model is considered effective for analyzing drone accidents, no previous studies have applied it to drone-specific incidents in either domestic or international research.

In this study, we adopt the definition by Kato et al. [10], which states that “human error is induced by the interaction between human characteristics and their surrounding environment,” and hence, we propose to develop a drone-specific accident analysis model based on H.F. Hawkins’ SHEL model. Constructing the model, we aim to establish an analytical framework for drone accidents that contributes to realize safer drone operations.

2. Objective

Drone-related accidents have not yet been sufficiently examined from the perspective of human error. Therefore, this study aims to develop a drone-specific accident analysis model based on past accident cases reported to the MLIT, and to clarify the usability of the proposed model.

3. Methods

3-1 Research subjects

Two datasets published on the website of the MLIT were selected for the study: the list of drone-related accidents and serious incidents reported to MLIT in FY2021 [3], covering the period from April 1, 2021 to March 31, 2022 (before the revision of the Civil Aeronautics Act), and the list of drone-related accident reports [6], covering the period from April 1, 2023 to March 31, 2024. A total of 42 cases were excluded from the analysis due to insufficient information, such as incidents where the outcome (e.g., “loss of control of the drone”) was reported but the cause was unclear, or where the report lacked the necessary details to be accurately classified using H.F. Hawkins' SHEL model. As a result, 109 cases were included in the final dataset for analysis.

3-2 Analysis of the current situation

We carefully examined the data obtained from the MLIT website-including an overview of each incident, the extent of drone damage, preventive measures, and additional notes-and classified each case according to which factors of H.F. Hawkins' SHEL model were applicable (multiple classifications were allowed). Subsequently, using the KJ method [17], three researchers(R.I, M.E, R.M) collaboratively identified and organized subcategories for each SHEL factor and performed the classification accordingly.

3-3 Development of a new model

Using the Edwards' SHEL model, the H.F. Hawkins' SHEL model, the m-SHEL model, the P-mSHELL model, and the St-mSHELL model, we analyzed the trends identified in the previous section to clarify the unique characteristics of drone-related accidents. Based on these findings, we developed a new model that incorporates these specific trends.

3-4 Case analysis using the new model

Using the drone-specific SHEL model developed in the previous section, we reclassified 109 accidents and serious incidents cases obtained from the MLIT website based on the newly proposed model and evaluated its effectiveness.

4. Results

4-1 Causal factors of reported accidents based on the SHEL model

Out of the 109 analyzed drone accidents and serious incidents cases, the contributing factors were classified based on the H.F. Hawkins' SHEL model. The results showed that 52 cases were related to Software, 42 to Hardware, 23 to Environment, 21 to Liveware (Personnel present on-site excluding the operator; hereinafter referred to as 'other personnel), and 38 to Liveware (operators) (**Fig.1**). A total of 177 contributing factors were identified, indicating that each case involved an average of 1.6 factors.

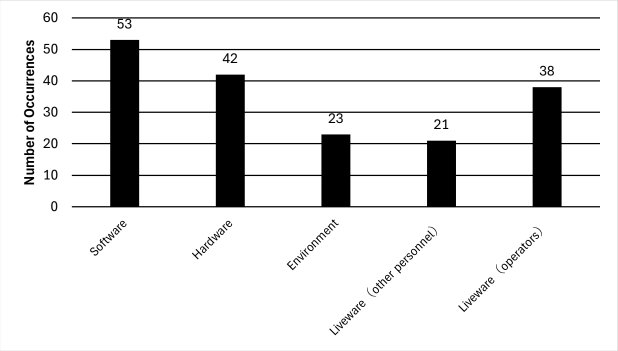

Fig.1 Analysis results based on H.F. Hawkins' SHEL model.

4-1-1 Software

The "Software" category was further classified into three subcategories. Among the 53 software-related cases, 30 were attributed to inadequate safety management, 16 to inadequate flight planning, and 7 to non-compliance with manuals (**Fig.2**).

The details of the cases are as follows:

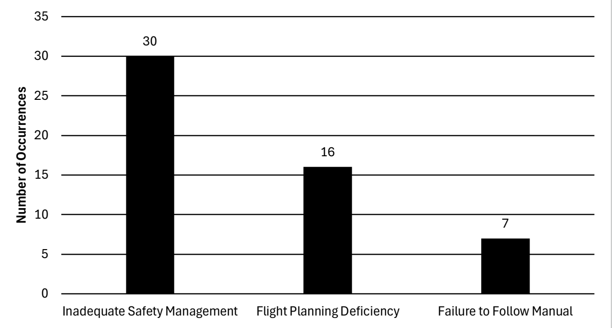

Fig.2 Classification results of software factors.

For inadequate safety management, reported cases included incidents where individuals came into contact with rotating propellers during flight or takeoff/landing, failure to maintain safe distances between the drone and the operator or other personnel, disabling obstacle detection functions without due caution, insufficient pre-flight coordination with assistants, and failure to conduct a proper risk assessment before flight, resulting in accidents.

Flight planning deficiency included failing to establish safe distances from obstacles, failing to designate appropriate takeoff and landing sites, failing to consider potential electromagnetic interference from radio towers or power lines, and failing to consider the drone's flight range, resulting in an inability to return to the designated landing site.

Incidents of failure to follow manual, reported incidents included continuing flight despite low battery warnings, failing to assign assistants when required, and flying beyond visual line of sight (BVLOS) flights without assigning an assistant.

4-1-2　Hardware

The "Hardware" category was further classified into eight subcategories. The number of cases in each category was as follows: "Communication Failure" (20 cases), "Battery-related Issues" (8 cases), "Software malfunction" (4 cases), "GPS error" (3 cases), "Rotor Failure" (3 cases), "Sensor Malfunctions" (2 cases), "Design Flaw" (1 case), and "Control device failure" (1 case) (**Fig.3**).

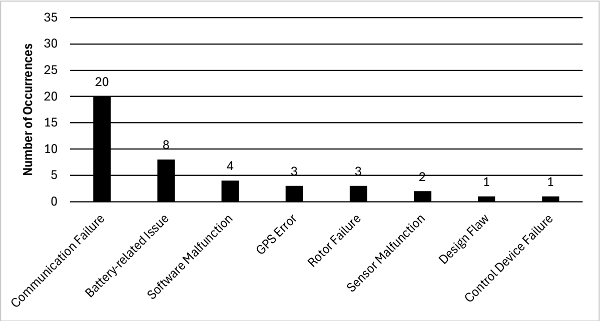

Fig.3　Classification results of hardware factors.

In the "Communication failure" category, reported incidents included sudden loss of radio signal and cases where communication failure resulted in loss of control of the aircraft.

Cases categorized under "Battery-related issue" included a sudden voltage resulting in a crash, and battery damage during flight resulted in loss of control and subsequent crash.

In the "Software Malfunction" category, cases included an unexpected switching to auto-landing mode resulting in a crash, a propulsion system error triggered an emergency landing mode resulting in a dive, and a sudden loss of aircraft control.

The "GPS Error" category included incidents where reduced GPS sensitivity made autonomous control difficult, crashes due to GPS failures that rendered the aircraft uncontrollable, and unstable GPS function that caused the aircraft to drift in unintended directions.

The "Rotor Failure" category included rotor failures in flight that resulted in crashes, as well as incidents where rotors separated in flight.

In the "Sensor Malfunction" category, cases included abnormal behavior of sensors at low altitude flight over water, that differed from their performance on land, which caused a crash; and failure of the aircraft's speed sensor during flight, resulting in loss of control and a crash.

The "Design Flaw" category involved a case where due to a design flaw, a fairing contacted an arm due to design deficiency, causing the arm to break and the aircraft to crash.

The "Control Device Failure" category included a case in which a malfunction in the control device during flight, causing the drone to disappear.

4-1-3　Environment

The "Environment" category was classified into four subcategories. Among the 23 environment-related cases, 18 were caused by wind, 3 by Radio wave or magnetic interference, 1 by Sunlight, and 1 by Bird

Strike (**Fig.4**).

Wind-related incidents included reports of drones being blown off course and crashing in sudden gusts of wind, collisions with gravestones while attempting to land in high winds, and drones being blown into building walls during inspections. For radio wave or magnetic interference, cases included signal interference caused by steel towers resulting in loss of control, abnormal drone behavior due to magnetic interference, and loss of control leading to crashes when flying near high-voltage power lines.

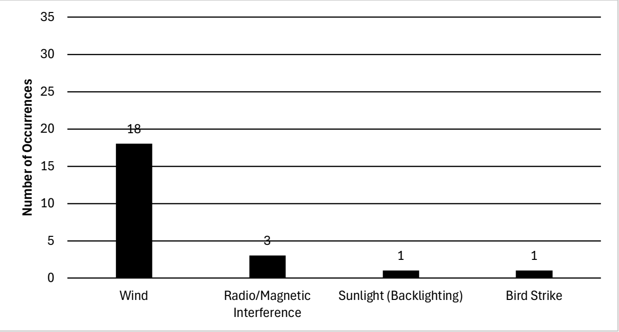

Fig.4 Classification results of environmental factors.

For sunlight, one report described a drone that was unable to detect telephone wires due to backlighting from the sun, resulting in a severed line.

For bird strike, there was a report of a drone inspecting a bridge over a river that collided with a bird and subsequently fell into the water.

4-1-4 Other personnel (liveware)

The "Liveware (other personnel)" category was classified into six subcategories. Among the 21 related cases, 12 were caused by coordination errors, 8 were caused by inadequate monitoring, 1 was caused by distraction by a third party(**Fig.5**).

Incidents of coordination errors included failure to notice a signal from the assistant, causing the drone to pass the intended stop point and collide with power lines; failure to hear or receive signals due to distance, causing collisions with obstacles; failure to properly coordinate with the assistant, causing the drone to fly past the turn point and strike telephone wires; and improper positioning of the assistant, causing both the operator and the assistant to lose visual contact with the drone, resulting in a crash.

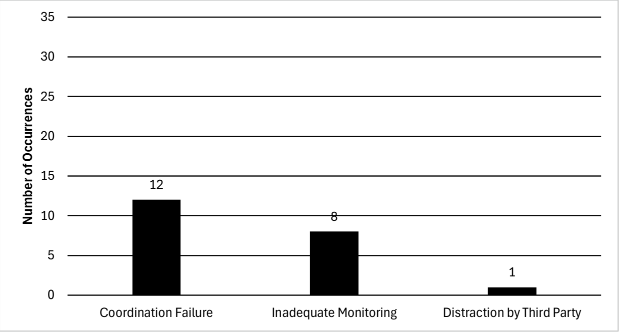

Fig.5 Classification results of other personnel (liveware) factors.

In cases of inadequate monitoring, incidents included assistants being present but engaged in other tasks, neglecting to monitor the drone; and assistants standing too close to the operator and focusing on the control screen, causing them to miss surrounding obstacles and leading to a collision with trees.

For distraction from a third party, one case involved a third party speaking to the operator during flight, causing the operator to lose focus and resulted in a crash.

4-1-5 Operator (liveware)

The "Liveware (operator)" category was classified into three subcategories. Among the 38 related cases, 24 were attributed to Operational Error, 11 to Visual Recognition Error, and 3 to incorrect drone settings (**Fig.6**).

Operational errors reported included crashes due to incorrect operation, collisions with people or objects caused by operator error, unintentional activation of

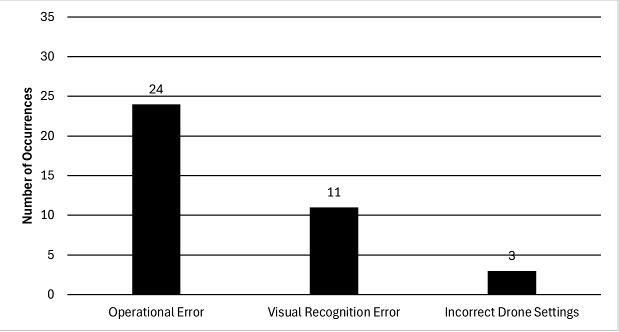

Fig.6 Classification results of operator (liveware) factors.

automatic mode resulting in contact with telephone wires, failure to properly switch from automatic to manual mode during flight resulting in a crash, deactivation of obstacle sensors resulting in collisions, and inadvertent switching of flight modes during flight resulting in loss of control and subsequent crash.

Incidents of visual mismatch included crashing into a pond due to misjudging altitude while flying near the water's surface; losing visual contact with the drone in mountainous areas, resulting in a crash into trees; collisions with power lines that blended into the background; crashes caused by inability to see telephone wires due to backlighting; distraction while flying beyond visual line of sight (BVLOS) flight while focusing on photography, resulting in a collision with trees; and crashes caused by excessive focus on the controller screen while descending, resulting in a collision with a nearby vehicle.

4-2 Development of the analytical model

In developing the analytical model, we examined the usefulness of the H.F. Hawkins SHEL model. Analysis using this model revealed that drone accidents had an average of 1.6 contributing factors per case.

The most common drone-specific issue was inadequate safety management, which accounted for 30 cases. Because safety management is fundamentally a pre-flight responsibility and a top priority, many of these accidents were considered preventable if proper safety protocols had been followed. Therefore, we determined that safety should be positioned as the highest level concept in the model. Inspired by the m-SHEL model, we replaced the "M" for "Management" with "S: Safety" and placed it at the top of the model.

In addition, since 20 cases were related to communication failure, a serious and drone-specific operational risk, we added "R: Radio Wave (Communication/Electromagnetic Interference)" as a new component.

The traditional H.F. Hawkins SHEL model does not distinguish between the operator and other personnel under the "Liveware" component, which can lead to confusion in classification. To resolve this, we explicitly defined "Operator" as a separate component, distinguishing it from "Liveware" (other personnel), thus enhancing clarity in categorization.

The final model consists of the following elements: Safety, Software, Hardware, Operator, Environment, Liveware, and Radio wave, and was named the S-SHOELR model. In its visual structure, Operator is positioned at the center, surrounded by the other elements to illustrate their mutual influence. In addition, Safety encircles the entire model to convey the principle that safety should take precedence over all other factors (Fig.7).

Elements	Content
S : Safety	The safe operation of drones requires key elements such as the implementation of safety measures, risk assessment, flight path planning, emergency response protocols, and pre-flight checks.
S : Software	Items that are not formalized as flight plans, operation manuals, or relevant legal regulations.
H : Hardware	Technical factors mainly involving the drone itself, its associated systems (including software applications), and its control devices may pose safety risks.
O : Operator	Factors pertaining to the drone operator include operational proficiency, human factors, and physiological condition.
E : Environment	Environmental considerations include weather conditions (e.g., rain, wind, illumination, and temperature); airborne obstacles (e.g., birds and insects); ambient noise; available flight space; and flight duration.
L : Liveware	Factors involving individuals other than the operator include personnel providing instructions or guidance and uninvolved third parties.
R : Radio wave	Factors involving communication disruptions, electromagnetic interference, and magnetic field disturbances.

Fig.7 The developed S-SHOELR model.

4-3 Analysis of accident cases using the S-SHOELR model

A total of 109 accident cases were analyzed using the S-SHOELR model, following the same procedure as with H.F. Hawkins' SHEL model. The results showed the following number of cases for each factor: Safety-30, Software-23, Hardware-22, Operator-38, Environment-20, Liveware (other personnel)-21, and Radio Wave (communication)-22 (**Fig.8**).

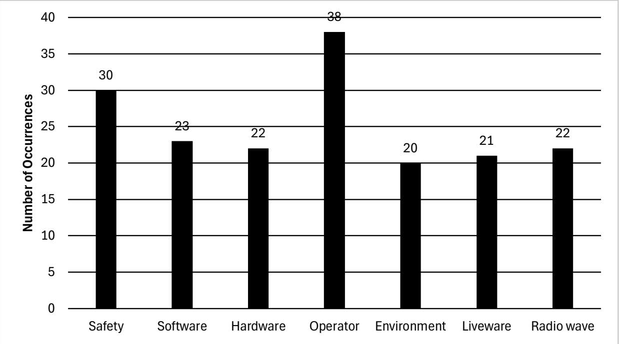

Fig.8 Analysis results using the S-SHOELR model.

5. Discussion

The H.F. Hawkins' SHEL model has been widely applied across various industries. In this study, the model was used to analyze past drone-related accident cases and found that, on average, each case involved 1.6 contributing factors. This indicates that drone accidents are typically not caused by a single factor, but rather by a complex interaction of multiple elements. Therefore, the use of the SHEL model for drone accident analysis is considered effective.

When the 109 accident cases were analyzed by factor using the H.F. Hawkins' SHEL model, Software was the most frequently identified category, accounting for 53 cases (48.6%). Within this category, inadequate safety management alone accounted for 30 cases, representing 27.5% of all drone accidents. This suggests that nearly one-third of the accidents could potentially have been prevented if proper safety management had been implemented, underscoring its critical role in safe drone operations.

While the existing H.F. Hawkins' SHEL model does provide meaningful insights into drone accidents, it categorizes drone-specific factors such as safety management deficiencies under "Software" and communication failures under "Hardware." This concentration causes other contributing factors limiting the model's ability to fully support accident prevention through comprehensive analysis.

In response, we proposed a new model tailored to drone operations: the S-SHOELR model. In this model, the "Management" component from the m-SHELL model is replaced by "Safety", explicitly placing safety as the top priority. Furthermore, the newly introduced factor "Radio wave (Communication)" enables the analysis of drone-specific risks associated with electromagnetic interference and loss of communication.

Compared to the H.F. Hawkins' SHEL model, the S-SHOELR model also clearly distinguishes between the Operator and other Liveware (other personnel)—a distinction not made in the original model—which improves classification accuracy. Upon reclassifying the 109 accident cases using the S-SHOELR model, 38 cases were attributed to the operator and 22 to Radio wave failures, reflecting a more accurate representation of real-world drone operations.

Additionally, the visual design of the S-SHOELR model positions Safety as the outermost layer surrounding all elements, emphasizing that safety should take precedence over all other considerations. This structure enhances the model's educational value and usability of the model in operational training and awareness activities.

By focusing specifically on drone-related risk factors, the S-SHOELR model can be used not only for post-accident analysis but also for pre-flight risk assessment. Currently, Japan's Civil Aeronautics Act requires operators to submit a risk analysis and evaluation when applying for permission to conduct Level 4 drone flights, but not for lower-level flights. However, given that 27.5% of drone accidents are related to safety management issues, a simplified method for conducting risk assessments is needed. The S-SHOELR model can effectively fulfill this role.

In addition, incorporating the S-SHOELR model into academic training programs for certified unmanned aircraft pilots could enhance hazard prediction training. This would deepen understanding of hidden risks during drone flight operations and contribute to the prevention of future accidents.

6. Conclusion

In this study, we developed a drone-specific accident analysis model called the S-SHOELR model, based on H.F. Hawkins' SHEL model and using past accident cases. The key features of the S-SHOELR model are its structural foundation on the SHEL model, the addition of two new components- "Safety" and "Radio wave (communication)", and the explicit distinction between the Operator and Liveware (other personnel).

When the model was applied to analyze accident cases, it was found that the largest number of accidents were attributed to the operator, followed by issues related to safety management and communication failures. These findings demonstrate that the S-SHOELR model is a useful tool for analyzing drone accidents.

Moreover, the S-SHOELR model is not limited to post-accident analysis. It is also expected to be applied as a risk assessment tool for Level 3 or lower drone flights, as well as an educational tool to support the safe operation of drones.

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インドネシアにおける災害時ドローン運用法の開発と評価

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近年，防災分野におけるドローンの活用は日本国内で急速に普及しており，特に地震や津波，土砂災害など，災害直後に人が立ち入ることが困難な被災地において，短時間で俯瞰的な情報を取得できるという利点から，運用が増加している。災害時においては，迅速な被災状況の把握と救助活動の効率化が求められるが，日本で広く導入されている災害対応用ドローンの運用方法は，同様に災害が頻発するインドネシアにおいては未だ遅れており，ドローン運用に関する体系的な研究や議論も限られている。さらに，日本国内においても，災害時のドローン運用法は体系的に確立されたものがなく，様々な視点からの使用法や新技術に関する議論がなされているのみである。このため，体系的に開発された災害時のドローン運用法をインドネシアに導入し，その有用性を実証することが必要であると考えられる。本研究では，災害時におけるドローン運用法を開発し，インドネシアにおける運用実態を調査することで，その有用性を明らかにすることを目的とする。調査の結果，ドローン運用法に関する講義および防災訓練に参加した者は，災害時におけるドローン活用の必要性を認識し，ドローン運用法に対して高い評価と期待を示した。この結果から，災害時におけるドローン運用法が有用であることが確認された。災害時のドローン運用法は，新しく開発された手法であり効果的かつ効率的で信頼性の高い災害時のドローン活用のために必要である。しかし，操縦に対する不安感や関連機関との調整は今後の課題として挙げられており，いつ起こるかわからない大規模災害に備え人材育成や事前調整が重要となるこのような議論は，災害が非常に多い日本とインドネシアにとって適切な災害対策環境を生み出し，相互協力によって防災・減災の一助となると言える。

Keywords: インドネシア，ドローン，災害対応，減災，リスクマネジメント

Development and Evaluation of Drone Operational Methods for Disasters in Indonesia

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In recent years, drones have become increasingly prevalent in disaster prevention efforts in Japan, particularly in areas affected by earthquakes, tsunamis, and landslides. These areas are often inaccessible to humans immediately following a disaster. Drones offer the advantage of quickly obtaining aerial information, which has led to an increase in their usage. During disasters, prompt assessment of affected areas and efficient rescue operations are eminent. However, although Japan has widely adopted drones for disaster response, Indonesia, a country also frequently affected by disasters, has not developed operational methods + . Furthermore, there is limited systematic research or discourse regarding drone operations in disaster contexts in Indonesia. In Japan, there is also no established, systematic approach to operating drones during disasters. Instead, discussions primarily focus on various operational methods and new technologies. Therefore, it is essential to introduce a systematically developed disaster drone operation method in Indonesia and demonstrate its effectiveness. This study aims to develop such a method and investigate its effectiveness when implemented in Indonesia. Results of the investigation revealed that participants in drone operation courses and disaster prevention drills recognized the necessity of utilizing drones during disasters and expressed high expectations for the proposed operational method. These results indicate the effectiveness of the developed drone operation method for disaster scenarios. Moreover, the newly developed method is considered effective, efficient, and reliable for utilizing drones in disaster response. However, concerns were raised about the proficiency of drone operations and coordination with relevant agencies, which will need to be addressed in the future. To prepare for future large-scale disasters, it is crucial to focus on training personnel and conducting pre-disaster coordination. These discussions are vital for establishing an effective disaster prevention and reduction environment in both Japan and Indonesia. Through mutual cooperation, these issues can be resolved, thereby enhancing disaster prevention and reduction efforts.

Keywords: Indonesia, Drone, Disaster Countermeasures, Risk Reduction, Risk Management

1. Introduction

Located at the intersection of the Alps-Himalayas and Pacific Rim orogenic belts, Indonesia is known to experience a large number of natural disasters in connection with the earthquakes. The Indonesian people have suffered tremendously from various disasters, including the 2024 eruption of Mount Luang in Sangihe, North Sulawesi, the 2005 Central Java earthquake, and the 2004 Indian Ocean tsunami that occurred in conjunction with the earthquakes. In particular, the 2004 Sumatra-Aceh earthquake and Indian Ocean tsunami left more than 220,000 people dead or missing [1]. In addition, about 140,000 houses were destroyed in the 2004 Sumatra earthquake and about 100,000 houses in the 2018 Central Sulawesi earthquake, resulting in a very large number of deaths [2].

Disaster response in Japan, which like Indonesia suffers from a variety of disasters, is based on the Disaster Countermeasures Basic Law, which was enacted after the response experience gained in the Typhoon Isewan in 1961. It killed about 5,000 people and caused extensive damages, and is used for the betterment of disaster risk reduction, disaster relief, and recovery and reconstruction [3], especially after the 1995. In particular, the experience of the Great Hanshin-Awaji Earthquake of 1995 provided an opportunity for a major shift in disaster response policy. The Great Hanshin-Awaji Earthquake killed about 6,000 people, of whom about 77% died from suffocation or crushing [4], and the danger of house collapse is extremely important in disaster countermeasures. It was also found that the percentage of survivors among those rescued on the day of the disaster was 75%, but the survival rate dropped significantly to 24% after 24 hours, 5% after 48 hours, and 5% after 72 hours [5].

As described above, it is clear that rapid rescue from collapsed houses caused by earthquakes, tsunamis, and typhoons greatly improves the survival rate, but since the fire department, police, and Self-Defense Forces do not have enough manpower to respond to all disaster situations spread over a very large area, rescue was carried out by citizens using various hands-on equipment. As one of the rapid rescue methods, the use of drones to assess the disaster situation and quickly locate those who are in need of rescue has been promoted. In recent years, the use of drones in disaster management has spread throughout Japan, especially in disaster areas where it is difficult for people to enter immediately after an earthquake, tsunami, landslide, or other calamities, as drones can easily obtain bird's eye view information in a short time. According to a survey [6] on drone ownership, 726 municipalities and 201 fire departments nationwide in Japan own drones, and the number of fire departments that own drones is expected to increase in the future.

Indonesia has the largest population in the ASEAN (Southeast Asia) region, and its population is expected to grow continuously until 2050. It is a country with remarkable economic growth [7]. With this economic growth and population growth, the demand for houses is increasing. However, the masonry houses that are currently being built in large numbers in Indonesia may not be strong enough or durable enough to withstand natural disasters. As a result, they collapse during disasters, resulting in casualties and trapped people. The main cause of casualties due to collapsed houses is the widespread use of brick masonry construction, which is extremely vulnerable to earthquakes [8]. Another factor that increases the number of casualties is that the debris from collapsed houses is in pieces and takes a lot of time and effort to remove. Therefore, rapid assessment of the disaster situation and rapid allocation of rescuers are inevitable. However, the introduction of disaster management drones, which are widely used in Japan, are still advancing in Indonesia, and there are few reports on the operation of drones. Even in Japan, there is no systematically developed operation method for drones used in disasters, and there are only discussions about the use and new technologies from various experts. Therefore, it is necessary to introduce a systematically developed operational method for drones in disasters to Indonesia and clarify its usefulness.

Budi Luhur University (UBL), where the research for this study was conducted, has a Department of International Relations in the Faculty of Social and Political Sciences and has a strong disaster preparedness research and education program. In the Republic of Indonesia, the Ministry of Social Affairs, together with the National Research and Innovation Agency Badan Riset dan Inovasi Nasional (BRIN), has established the Taruna Siaga Bencana Youth Group for Disaster Preparedness (TGD), a public-private partnership for disaster preparedness. TAGANA has about 200,000 members and is involved in civil protection activities in the event of a disaster. Its activities include food and material stockpiling, disaster preparedness training and education, disaster food supply, and rescue operations. Therefore, we believe that the drone operation methods developed in this study with disaster drills at UBL may contribute to the reduction of rescue time and reduce the number of casualties.

Therefore, the purpose of this study is to develop a drone operational method in disaster management and to clarify the usefulness of the drone operational methods through a lecture on the drone operational methods in disaster management and a questionnaire survey of participants in a disaster management drill conducted at UBL in Indonesia.

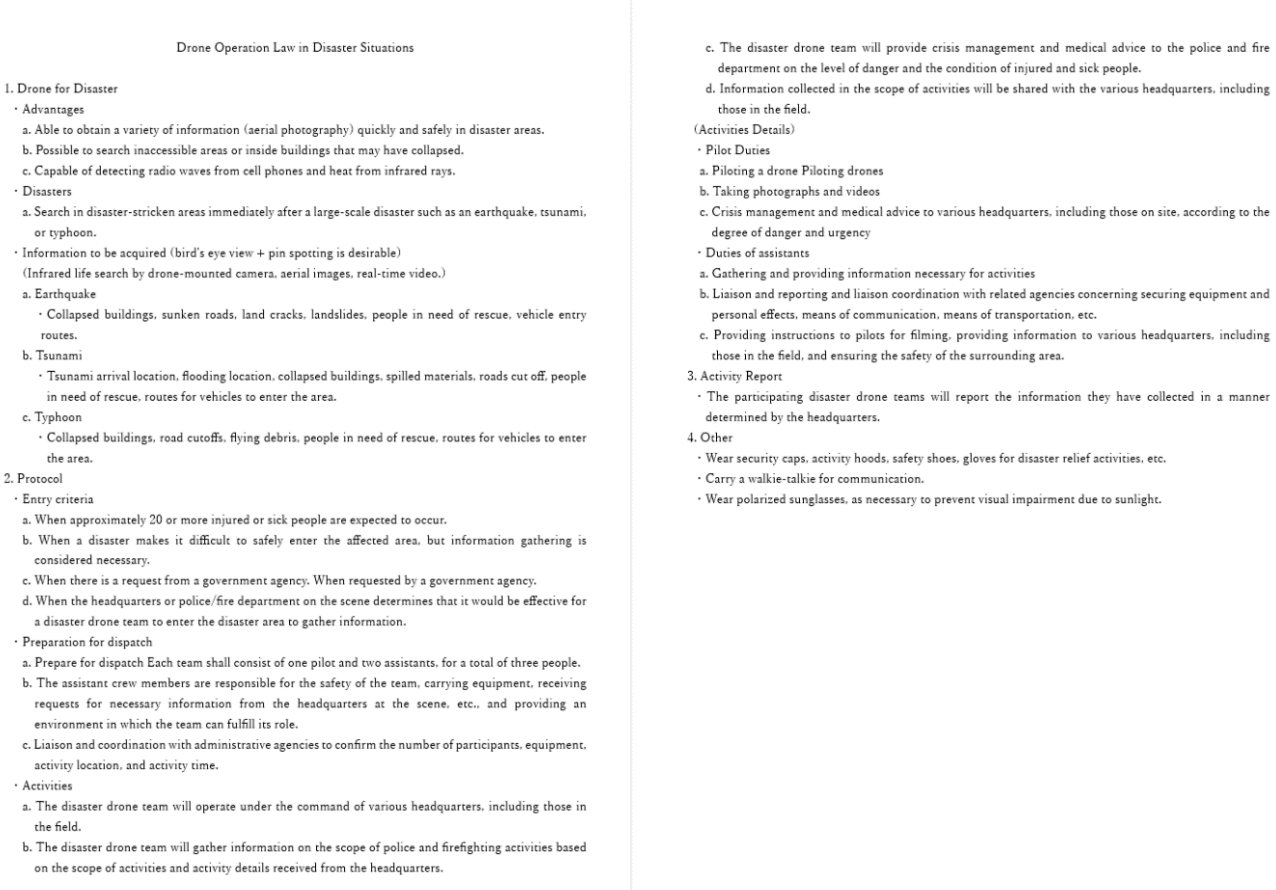
2. Methods

2-1 Survey population

The target population was 53 participants of the lecture on drone operation methods in disasters and disaster drills held at UBL in August 2024.

2-2 Development and use of drone operation methods in disasters

The authors systematically developed a drone operational method in disasters based on the Disaster Countermeasures Basic Act [3], disaster medical care protocols [9], and the authors' own experiences (**Fig.1**). The authors are experts with work experience as clinical engineers, paramedics, firefighters, disaster management (ICS: Incident Command System), and crisis management. They are also trained in disaster drone operations and first and second class unmanned aircraft pilots. The operational procedure consists of three sections: "Dispatch Criteria" for content related to dispatch, "Dispatch Preparation" for content related to team organization, and "Activities" for content related to reporting on activities at the scene. In addition, the advantages of drones and examples of information to be obtained at the time of each disaster were added as appendices. In lectures at UBL, we prepared and used lecture slides for explanation, adding examples of drone use with reference photos of information obtained to the drone operation methods we developed for use in disasters. In the disaster drill, a pilot and two assistants shared information in the lecture hall set up as the headquarters while ensuring safety based on the developed drone operation method in disasters, and simulated drone operations were conducted under instructions, and information from the drone was shared and summarized to the participants after the drill. During the disaster



Drone Operation Law in Disaster Situations

1. Drone for Disaster
  ・Advantages
    a. Able to obtain a variety of information (aerial photography) quickly and safely in disaster areas.
    b. Possible to search inaccessible areas or inside buildings that may have collapsed.
    c. Capable of detecting radio waves from cell phones and heat from infrared rays.
  ・Disasters
    a. Search in disaster-stricken areas immediately after a large-scale disaster such as an earthquake, tsunami, or typhoon.
  ・Information to be acquired (bird's eye view + pin spotting is desirable)
    (Infrared life search by drone-mounted camera, aerial images, real-time video.)
    a. Earthquake
      ・Collapsed buildings, sunken roads, land cracks, landslides, people in need of rescue, vehicle entry routes.
    b. Tsunami
      ・Tsunami arrival location, flooding location, collapsed buildings, spilled materials, roads cut off, people in need of rescue, routes for vehicles to enter the area.
    c. Typhoon
      ・Collapsed buildings, road cutoffs, flying debris, people in need of rescue, routes for vehicles to enter the area.
2. Protocol
  ・Entry criteria
    a. When approximately 20 or more injured or sick people are expected to occur.
    b. When a disaster makes it difficult to safely enter the affected area, but information gathering is considered necessary.
    c. When there is a request from a government agency. When requested by a government agency.
    d. When the headquarters or police/fire department on the scene determines that it would be effective for a disaster drone team to enter the disaster area to gather information.
  ・Preparation for dispatch
    a. Prepare for dispatch Each team shall consist of one pilot and two assistants, for a total of three people.
    b. The assistant crew members are responsible for the safety of the team, carrying equipment, receiving requests for necessary information from the headquarters at the scene, etc., and providing an environment in which the team can fulfill its role.
    c. Liaison and coordination with administrative agencies to confirm the number of participants, equipment, activity location, and activity time.
  ・Activities
    a. The disaster drone team will operate under the command of various headquarters, including those in the field.
    b. The disaster drone team will gather information on the scope of police and firefighting activities based on the scope of activities and activity details received from the headquarters.
    c. The disaster drone team will provide crisis management and medical advice to the police and fire department on the level of danger and the condition of injured and sick people.
    d. Information collected in the scope of activities will be shared with the various headquarters, including those in the field.
  (Activities Details)
  ・Pilot Duties
    a. Piloting a drone Piloting drones
    b. Taking photographs and videos
    c. Crisis management and medical advice to various headquarters, including those on site, according to the degree of danger and urgency
  ・Duties of assistants
    a. Gathering and providing information necessary for activities
    b. Liaison and reporting and liaison coordination with related agencies concerning securing equipment and personal effects, means of communication, means of transportation, etc.
    c. Providing instructions to pilots for filming, providing information to various headquarters, including those in the field, and ensuring the safety of the surrounding area.
3. Activity Report
  ・The participating disaster drone teams will report the information they have collected in a manner determined by the headquarters.
4. Other
  ・Wear security caps, activity hoods, safety shoes, gloves for disaster relief activities, etc.
  ・Carry a walkie-talkie for communication.
  ・Wear polarized sunglasses, as necessary to prevent visual impairment due to sunlight.

Fig.1 Developed drone operational methods in disasters.

preparedness drill conducted in this study, a DJI Mini 4 Pro (manufactured by DJI, with 2.4 GHz Wi-Fi, a maximum resolution of 48 MP, a 1/1.3-inch sensor, and GPS + Galileo + BeiDou) was used to capture aerial footage. Each team operated the drone for approximately 10 minutes to record the positions and conditions of simulated collapsed structures and evacuees moving toward designated shelters. The recorded information was then shared in real time with participants at the lecture room to facilitate situational awareness and informed decision-making as an emergency operations center.

2-3　Survey method

From August 22 to 25, 2024, a questionnaire was created in English and translated into Indonesian based on the Active Learning Classroom Design Tool [10] and distributed to the target participants as an anonymous survey.

2-4　Survey content

In order to evaluate the usefulness of drone operational methods in disaster, the questionnaire included nine multiple-choice items, including two items about the use of drones in disaster【Q1: Do you think it is necessary to use drones in disaster?】,【Q2: Do you think the information obtained using drones will be needed for rescue and disaster management?】, seven items about drone operational methods【Q3: Do you think it is necessary to establish the drone operational methods?】,【Q4: Was the level of lecture on drone operational methods appropriate?】,【Q5: By learning the drone operational methods, can you operate a drone in a disaster without anxiety?】,【Q6: Do you expect that the use of the drone operational methods will improve information acquisition capabilities in the future?】,【Q7: Do you think this drone operational methods can be commonly used in disasters in Indonesia and Japan?】,【Q8: Would you like to introduce the drone operational methods?】,【Q9: Can the drone operational methods be evaluated?】, The total number of items was 10, including 9 multiple-choice items and 1 free response item in【Q10: Please fill in the good and bad points after learning about the drone operational methods.】. Note that the choices were on a 5-point Likert scale of "agree-somewhat agree-normal-somewhat disagree-disagree." after learning about the drone operation methods.】. Note that the choices were on a 5-point Likert scale of "agree-somewhat agree-normal-somewhat disagree-disagree".

2-5　Analysis method

The results of the responses regarding the use of drones in disasters and drone operational methods were tabulated. Next, we used IBM SPSS Statistics Ver. 29 software to calculate the statistics for each of the two items on the use of drones in disasters and the seven items on drone operational methods. Cronbach's alpha coefficient was checked for the drone operation methods. Then, a factor analysis based on the principal factor method was conducted to examine the evaluation factors for drone use and drone operation methods in disasters. In addition, text mining analysis was performed using a Kh coder [11], hierarchical cluster analysis, and sentences were extracted and coded. Furthermore, content analysis based on the KJ method [12] was performed and coded, and similarities were combined to form subcategories at a higher level of abstraction. Categories were created by combining subcategories that had common meanings by further raising the level of abstraction. In classifying categories and subcategories, the researchers examined whether categories and subcategories were generated by focusing on the similarity of multiple codes, whether the category name was a direct expression of the free-text item, and whether there were any distortions or biases in interpretation or categorization. The three researchers who conducted the survey carefully examined the results to confirm their validity based on overall integrity.

2-6 Research ethics

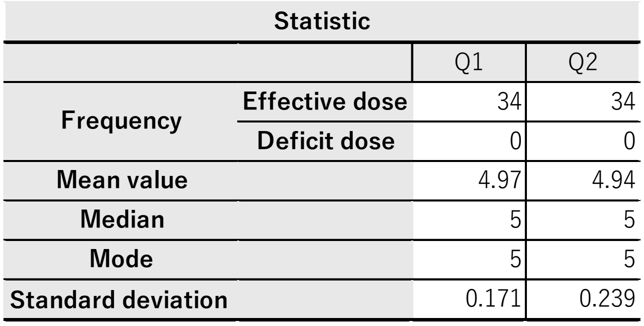
The study was approved by the BRIN and UBL ethics review boards, and a questionnaire was administered to participants in a lecture on the use of drones in disasters and a disaster exercise conducted at the university. In accordance with the international ethical guidelines of the Council for International Organizations of Medical Sciences, subjects were informed about the survey, told that the survey would be anonymous, that it would not be mandatory, and that any personal information obtained would not be used for any purpose other than the survey. The survey was administered after adequate explanation and consent was obtained from the subjects, and the response forms were collected only after consent was obtained. The data from this survey was anonymized and without names, so there was no benefit or risk to the research subjects.

3. Results

In order to clarify the evaluation and usefulness of the drone operation method in disasters, a questionnaire was sent to the participants of the drone operation method lecture and disaster drills conducted at UBL. 34 valid responses were received, for a response rate of 64%.

3-1 Trends in Drone Use in disaster

The tabulation results of the collected questionnaires show that 34/34 (100%) of the respondents answered “agree” or “somewhat agree” for【Q1: Do you think it is necessary to use drones in disaster?】$\bar{X}$ = 4.97 (SD 0.171). Next, for【Q2: Do you think the information obtained using drones will be needed for rescue and disaster management?】$\bar{X}$ = 4.94 (SD 0.239), 34/34 (100%) responded “agree” or “somewhat agree.” (**Fig.2**)



Statistic

		Q1	Q2
Frequency	**Effective dose**	34	34
	Deficit dose	0	0
Mean value		4.97	4.94
Median		5	5
Mode		5	5
Standard deviation		0.171	0.239

Fig.2 Basic statistics on the use of drones in disasters.

3-2 Trends in drone operational methods in disaster

Regarding【Q3: Do you think it is necessary to establish drone operation methods?】, 24/34 (71%) responded “agree” or “somewhat agree”. 24/34 (71%) of respondents answered “agree” or “somewhat agree” for【Q4: Was the level of lecture on drone operational methods appropriate?】, 27/34 (79%) of respondents answered “agree” or “somewhat agree” for【Q5: By learning drone operational methods, you can operate a drone in a disaster without anxiety?】. 33/34 (97%) of the respondents answered “agree” or “somewhat agree” to【Q6: Do you expect that the use of the drone operational method will improve the ability to obtain information in the future?】. 27/34 (79%) of the respondents answered “agree” or “somewhat agree” to【Q7: Do you think this drone operational method can be commonly used in disasters in Indonesia and Japan?】. 32/34 (94%) of the respondents answered “agree” or “somewhat agree” for【Q8: Would you like to introduce the drone operational methods?】. The highest mean was for the item【Q9: Can the drone operational methods be evaluated?】, with 34/34 (100%) responding “agree” or “somewhat agree”. The next item with the highest mean was【Q9: Can the drone operational methods be evaluated?】$\bar{X}=4.97$ (SD 0.171). The second was【Q8: Would you like to introduce the drone operational methods?】$\bar{X}=4.85$ (SD 0.500), and the third was【Q6: Do you expect that the use of the drone operational methods will improve the information acquisition capabilities in the future?】$\bar{X}=4.79$ (SD 0.538) (**Fig.3**).

The reliability coefficient for the Drone Operational Methods in Disasters scale was Cronbach's alpha (α) = .62. The results of the factor analysis of drone use and drone operational methods in disasters determined eigenvalues (2.384 for factor1, 1.425 for factor2, 1.112 for factor3, and 0.712 for factor4) from the Guttman-Kaiser criteria, and the number of common factors was 3. The cumulative contribution ratio was 70.301%. Factor analysis was performed on these factors using the method of least squares and varimax rotation. As a result, the first factor was【Q8: Would you like to introduce the drone operation methods?】and【Q9: Can the drone operation methods be evaluated?】, so the first factor was named “Evaluation of drone operation methods” factor. The second factor was the “Expectations of drone operational methods” factor, because it consisted of【Q3: Do you think it is necessary to establish drone operational methods?】,【Q5: By learning the drone operational methods, can you operate a drone in a disaster without fear?】, and【Q6: Do you expect that the use of drone operational methods will improve information acquisition capabilities in the future?】. The third factor was the “understanding of the drone operational law” factor, because it was【Q4: Was the level of lecture on the drone operational methods appropriate?】, and【Q7: Do you think that these drone operational methods can be commonly used in disasters in Indonesia and Japan?】(**Table1**).The reliability

Statistic								
		Q3	Q4	Q5	Q6	Q7	Q8	Q9
Frequency	**Effective dose**	34	34	34	34	34	34	34
	Deficit dose	0	0	0	0	0	0	0
Mean value		3.91	3.76	4.06	4.79	4.09	4.85	4.97
Median		5	4	5	5	5	5	5
Mode		5	4	5	5	5	5	5
Standard deviation		1.464	1.13	1.324	0.538	1.357	0.5	0.171

Fig.3　Basic Statistics on drone operational methods in disasters.

Table 1　Results of factor analysis of drone operational methods in disasters.

(data) Entry	1	2	3
Factor 1: Evaluation of drone operation methods			
Q8: Would you like to introduce the drone operational methods?	0.822	0.035	0.077
Q9: Can the drone operational methods be evaluated?	0.79	0.125	-0.07
Factor 2: Expectations for drone operational methods			
Q3: Do you think it is necessary to establish the drone operational methods?	-0.116	0.37	0
Q5: By learning the drone operational method, can you operate a drone in a disaster without anxiety?	0.364	0.75	0.168
Q6: Do you expect that the use of the drone operational methods will improve information acquisition capabilities in the future?	0.313	0.613	0.132
Factor 3: Degree of understanding of drone operational methods			
Q4: Was the level of lecture on drone operational methods appropriate?	-0.006	0.301	0.591
Q7: Do you think this drone operational methods can be commonly used in disasters in Indonesia and Japan?	0.011	-0.029	0.42

coefficient for the Drone Operational Methods in Disasters scale was Cronbach's $\alpha = .62$. The results of the factor analysis of drone use and drone operational methods in disasters determined eigenvalues (2.384 for factor1, 1.425 for factor2, 1.112 for factor3, and 0.712 for factor4) from the Guttman-Kaiser criteria, and the number of common factors was 3. The cumulative contribution ratio was 70.301%. Factor analysis was performed on these factors using the least squares method and varimax rotation. As a result, the first factor was【Q8: Would you like to introduce the drone operational methods?】and【Q9: Can the drone operational methods be evaluated?】, thus the first factor was designated as the "Evaluation of drone operational methods" factor. Factor 2 was the "Expectations of the drone operational method" factor, since it was【Q3: Do you think it is necessary to establish drone operational methods?】,【Q5: By learning the drone operational method, can you operate a drone in a disaster without anxiety?】, and【Q6: Do you expect that the use of the drone operational methods will improve information acquisition capabilities in the future?】. The third factor was the "understanding of the drone operational law" factor, since it was【Q4: Was the level of lecture on drone operational methods appropriate?】and【Q7: Do you think this drone operational methods can be commonly used in disasters in Indonesia and Japan?】(**Table 1**).

3-3 Trends in evaluation of free descriptions

Regarding the open-ended descriptions in【Q10: Please fill in the good and bad points after learning how to operate drones】, on the positive side, respondents answered that "we can confidently operate drones in disaster management", "the good news is that it is time efficient", and "drones can be very useful in assessing disaster victims". On the negative side, respondents answered that "not everyone can operate drones", "it is difficult to coordinate with relevant agencies because flights are regulated by the Air Force", and "it requires skill to operate drones". Next, **Figures 4** and **5** show the results of the hierarchical cluster analysis. The number of clusters was set to 5 for the good aspects of the drone operation method due to the plot attenuation status of the merging levels. Cluster1 was named "reducing unemployment and disasters" because it includes "unemployment", "reducing", and "disasters", etc. Cluster2 was named "Drones can search for victims" because it includes "can", "drones", "victims" and "search", etc. Cluster3 was named "We do drone management" because it includes "management," "help," and "we," etc. Cluster4 was named "Positive side" because it includes "side" and "positive", etc. Cluster5 was named "New technology is good for disasters" because it includes "news", "good" and "technology", "disaster", etc., and was classified into the above five component concepts. For the bad drone operation method, the number of clusters was set to 4. Cluster1 was named "Drones are used in disasters" because it includes "by," "drones," "disaster," and "use," etc. Cluster2 was named "Negative Emotions" because it includes "not", "are", and "difficult", etc. Cluster3 was named "Flaw of drone" because it includes "drone", "bad" and "point". Cluster4 was named "Who can use drones?" because it contains "who", "can" and "drones".

Next, as a result of the content analysis, we were able to create three categories of good points of drone operational methods in disasters: "advantages of drones," "benefits of operational methods," and "ripple effects of operational methods". Seven subcategories were also identified: "Safety and speed", "Search for disaster areas", "Victim assessment", "Understanding of operational methods", "Expectations of operational methods", "Disaster response", and "Measures against unemployment" (**Table 2**).

Three categories could be created for the bad points of drone operation methods in disasters: "basic knowledge of drones", "legal issues", and "restrictions on use". Six subcategories were also identified: "Inadequate knowledge", "Piloting skills", "Military issues", "Coordination with relevant agencies", "Bad

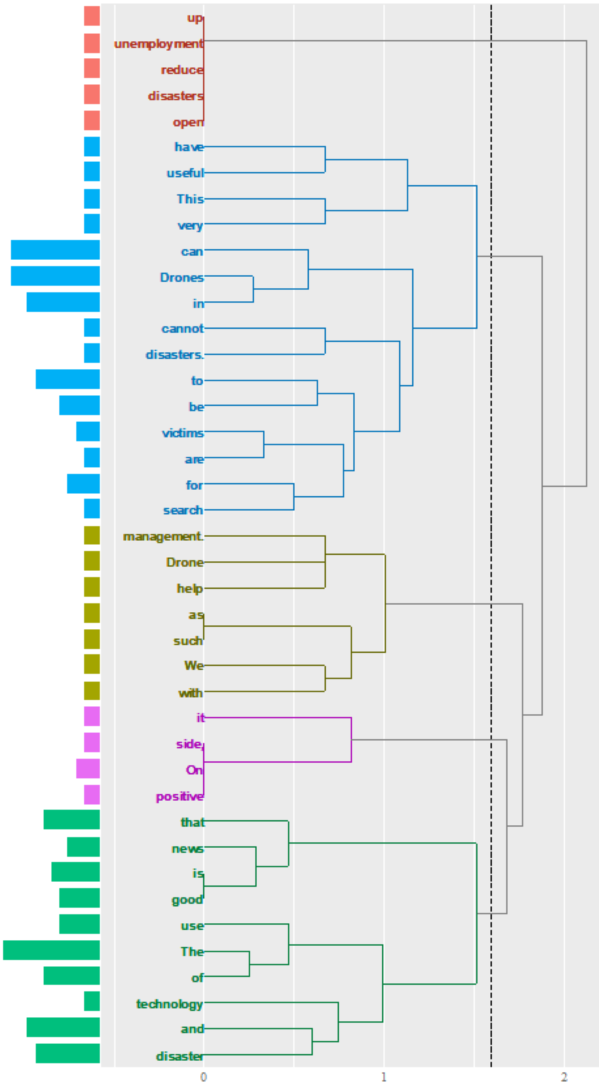


Fig.4　Results of hierarchical cluster analysis of good points.

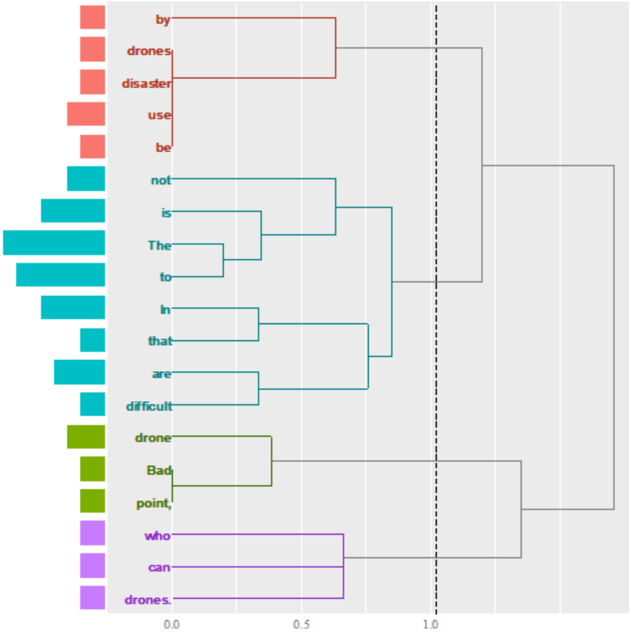


Fig.5　Results of hierarchical cluster analysis of bad points.

weather conditions", and "Performance" (**Table 3**).

4. Discussions

In this study, a lecture on drone operation methods and a questionnaire survey of disaster drill participants were conducted to clarify the usefulness of drone operation methods in disasters. Various studies have been conducted on the use of drones in disasters in both Japan and the Republic of Indonesia, reporting their high effectiveness in transporting medical supplies immediately after a disaster [13,14] and examining disaster relief methods using drones [15], but there are still few studies on operational methods. In the EU, the European Aviation Safety Agency (EASA) conducts a risk assessment called SORA (Specific Operational Risk Assessment). This is a risk assessment for operations in the specific category (high-risk flights such as flights out of sight and flights over third parties), which corresponds to Japan's specific flights, and does not examine operational methods in the event of a disaster. Drone operations involve various risks and must be effective, efficient, and reliable. However, it can be said that there is an urgent need to develop an appropriate operational method for the use of drones in disasters, where they are highly useful, because it is believed that there is not enough discussion on operational methods.

Table 2　Results of content analysis of good points of drone operational methods in disasters.

		Good points of drone operational methods in disasters
Category	**Subcategory**	**Code**
Advantages of drones	Safety and speed	Safety and speed Direct and rapid information can be obtained by using drones
		Safe reach to unreachable points
		Searching for victims who cannot be reached by human power due to natural disasters can be easily carried out by drone operations
		Able to locate the location of a disaster more quickly and accurately with drone technology
	Searching for disaster areas	Found useful to search the field
		Disaster victims, the post-disaster impact in areas that are difficult to access during a disaster, and the condition of the disaster area
		Helpful in dealing with disaster situations, such as locating victims, finding evacuation routes, and mapping disaster management
	Assessment of victims	Very useful for victim assessment
		Easy to find victims and quickly map the damage
		Helpful to search for victims in areas where rescuers cannot get to them
Benefits of operational methods	Understanding of operational methods	Other uses of drones such as rescue and disaster information
		Gained an understanding of the uses and benefits of drones in disasters
		Means of obtaining information on the use of drones in disaster management
	Expectations for operational methods	We can operate drones in disaster management with peace of mind
		This lecture was very good
Ripple effects of operational methods	Disaster response	Disaster response Time efficient
		Use of technology can easily support disaster response
	Measures against unemployment	Use of drones during disasters will reduce unemployment and lead to employment

Table 3　Results of content analysis of bad points of drone operational methods in disasters.

		Gad points of drone operational methods in disasters
Category	**Subcategory**	**Code**
Basic drone knowledge	Insufficient knowledge	Operating a drone requires specialized knowledge
	Piloting skills	Drone operations are difficult to understand for people who are not mechanically inclined
		Not everyone uses drones
		Need people who can handle drones
		Skills are needed to operate drones
Legal issues	Military issues	Drones are regulated by the Air Force in some places
	Coordination with relevant agencies	In some cases, drones are used only by relevant agencies
		Special training is needed on the use of drones for disaster management
Restrictions on use	Poor weather conditions	Weather can be an obstacle to drone operations
	Performance	Some types of batteries cannot be used for long periods of time
		Requires funds for capital investment

4-1　Trends in drone utilization in disaster

All respondents selected “agree” or “somewhat agree” for both【Q1】and【Q2】regarding the use of drones in disasters. Drones are well known for their use in the opening ceremonies of the Tokyo and Paris Olympic Games, and people around the world are aware of their convenience. The wide range of examples of their use suggests that respondents believe drones are necessary in disasters. In particular, Japan and the Republic of Indonesia, countries prone to natural disasters, are constantly researching the development of tools for safe and rapid disaster response [13,14] and are thought to recognize the need for new and useful technology.

4-2 Trends in drone operational methods

For drone operation methods, the mean scores were high for items【Q6】,【Q8】, and【Q9】. The factor analysis results for these items indicate that【Q8】and【Q9】were categorized as Factor 1, "Evaluation of drone operation methods," and【Q6】was categorized as Factor 2, "Expectations of drone operation methods," indicating a high evaluation and expectation of drone operation methods. Currently, the use of drones in disaster management is expected to increase due to the increasing risks of major disasters, such as the effects of global warming on tropical cyclones [16], and the Ministry of Land, Infrastructure, Transport and Tourism has pointed out the need to use drones in the initial response to major disasters [17]. However, with the current focus on the use of drones, it is important to consider appropriate operational methods to promote the use of drones in future disasters.【Q5】and【Q7】had the next highest average scores. In particular,【Q7】was categorized as Factor 3, "Understanding of drone operation methods," which can be interpreted as understanding of drone operation methods and recognition that they can be used for disaster response in the Republic of Indonesia. However, it is reported that the current disaster response system in the Republic of Indonesia does not work well in terms of the lack of disaster prevention regulations and the need to inform the local community [18]. In terms of informing the public, the drone operation method developed in this study needs more time to be understood and disseminated, as evidenced by the low mean of the item in【Q4】. It is urgent to consider measures to make the drone operation methods developed in this study widely available to the general public. In this study, a disaster drill was conducted after the lecture on drone operation methods, and the participants experienced how to operate a drone in the event of a disaster. This suggests that conducting a lecture on drone operation methods and a disaster drill with hands-on experience at the same time can help raise awareness of drone operation methods in disasters and promote the adoption of drones in disasters.

4-3 Trends in the evaluation of free descriptions

Next, as a result of content analysis, we were able to create three categories for good points of drone operational methods in disaster: "Advantages of drones", "Benefits of operational methods", and "Ripple effects of operational drones", indicating a "Sense of expectation for the drone operational method in disaster", suggesting that the presentation of reference cases in the drone operational methods lecture and the disaster training conducted at the same time. This suggests that the presentation of reference cases in the drone operational methods lecture and the disaster prevention training conducted at the same time deepened the understanding of the methods and the expectation for the use of drones. In addition, three categories of shortcomings of drone operation methods in disasters were identified: "basic knowledge of drones," "legal issues," and "limitations of use," which indicate "a sense of fear about the use of drones in disasters." Analysis of the codes listed as problems revealed that respondents felt uncomfortable operating drones and coordinating with related organizations. Analysis of the codes listed as problems revealed that respondents felt uneasy about operating drones and coordinating with related organizations. This is an item that is not implemented in drone operational methods lectures or disaster drills, and is an extremely important perspective in actual operations. Additionally, preliminary survey results indicated that participants had little to no prior experience with drone operations. The lack of coordination with related organizations in the use of drones in disasters in Japan, as well as the lack of use of drones in disasters, has also led to an urgent need for improvement in this area. This research must also improve this problem in order to disseminate the methods of using drones in disasters and promote their use.

4-4 Feasibility and future outlook of drone operation laws for disaster response in different countries

Indonesia, the target region of this study, shares similar geographical characteristics with Japan in that it is located along the Pacific Ring of Fire and is prone to frequent natural disasters, such as earthquakes, tsunamis, and volcanic eruptions. However, delays in the development of disaster prevention infrastructure and insufficient public awareness of disaster risk reduction due to the prioritization of economic growth pose significant challenges to the effectiveness of disaster management. In particular, systematic exploration and institutional development regarding the use of drones in disaster situations have not yet been adequately addressed. In this context, establishing an appropriate operational framework for drones in disaster management could significantly enhance disaster response capabilities.

In countries where the use of drones for disaster management is promoted, guidelines have been established to ensure safety and operational efficiency. For example, the United States Federal Aviation Administration (US-FAA) implemented the “Drone as First Responder (DFR)” program in accordance with 14 CFR Part 107 [19], involving one operator and one assistant. Similarly, the United Kingdom follows the “Unmanned Aerial Vehicle (UAV) and Drone Usage Policy [20],” with a similar personnel setup. Japan's Fukushima Robot Test Field (RTF) [21] guidelines recommend one operator and a safety manager to oversee the entire flight. For beyond-visual-line-of-sight (BVLOS) operations, an additional assistant is required. These guidelines specify necessary personnel configurations, operational conditions, and no-fly zones to ensure safety and minimize the risk of accidents during drone operations.

This study proposes an operational framework involving a three-person team: one operator and two assistants responsible for safety management, equipment handling, coordinating with relevant agencies, and collecting and disseminating data. The team is designed to deploy immediately after a disaster and collaborate with emergency services, such as fire, police, EMS, and military, to efficiently and promptly conduct disaster response, rescue operations, and information gathering. In conclusion, the operational models from other countries and the framework developed in this study complement each other. Integrating both approaches can establish a more effective disaster response system. The outcomes of this study are expected to serve as a versatile operational model applicable to other countries with high disaster risk and that could potentially be adopted internationally.

5. Conclusion

The purpose of this study was to determine the effectiveness of drone operational methods developed for disaster response. After implementing these methods in lectures and disaster drills at UBL, a survey was conducted. The results showed that participants recognized the necessity of using drones in disasters and highly evaluated and expected the operational methods. Similarly, hierarchical cluster and content analyses showed high evaluations and expectations for the methods, indicating their usefulness. However, this study has limitations because the relationship between operational capabilities in Indonesia and identified problems has not been verified. Therefore, it is necessary to utilize and evaluate these methods in real disasters in the future. The newly developed operational methodology for drones in disaster scenarios is essential for the effective, efficient, and reliable deployment of drones during such events. Comprehensive details of this methodology will soon be publicly available through a dedicated online platform. Nevertheless, concerns about operating drones and coordinating with relevant agencies remain challenges to be addressed. Due to the unpredictability of large-scale disasters, focusing on human resource development and pre-disaster coordination is crucial. Thus, our goal is to create a collaborative framework with Japan’s technical aid agency (ex. JICA), Indonesia’s Ministry of Social Affairs, and TAGANA to support the development of operational methodologies, infrastructure, and institutional frameworks. These discussions are expected to foster an effective disaster management environment in Japan and Indonesia, both of which experience frequent disasters.

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